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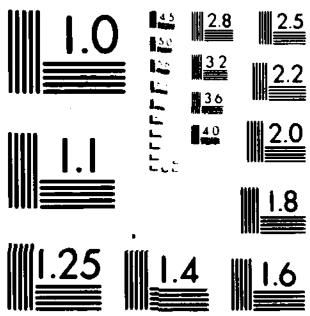

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FAA-RD-80-53

INTERFERENCE AND NOISE IN AND ADJACENT TO THE LORAN-C SPECTRUM AT AIRPORTS

ADA086043

MAY 1980

U.S. DEPARTMENT OF TRANSPORTATION

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16. Abstract

Electrical noise and interference in the LORAN-C frequency band was measured at two rural airports in Vermont and a major airport in Boston, Mass. The purpose of the test program was to determine the potential interfering sources that could affect the proper operation of the radio navigational system, LORAN-C, when it is used for non-precision approaches and terminal and en route navigation. Although no significant interference was observed, several continuous wave transmissions were identified in the frequency band adjacent to the LORAN-C band.

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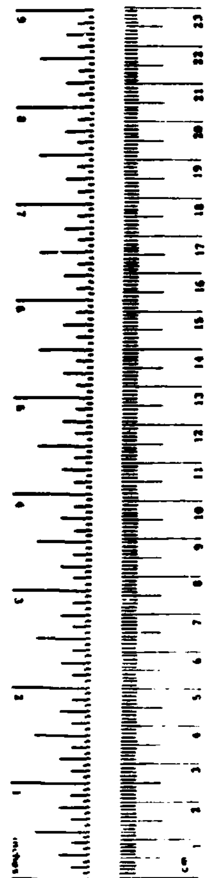
PREFACE

This report dicusses the noise and interference measured in the LORAN-C band at a major metropolitan airport, Logan, in Boston, Massachusetts, and at two rural airports in Vermont. This work was done for the Federal Aviation Administration as part of its continuing investigation of the applicability of the LORAN-C radio navigational system to non-precision approach and en route electronic navigation for aircraft.

METRIC CONVERSION FACTORS

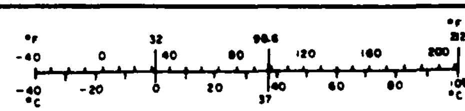
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

A series of measurements were made at the Burlington and Montpelier (Vt.) airports and at Logan International in Boston, Ma. to characterize the RF electrical noise and interference environment of LORAN-C radio navigational signals at both a small rural airport and a large metropolitan one. A spectrum analyzer connected to an active antenna was used to measure noise and interference. The acquisition time and performance of several LORAN-C receivers were observed.

LORAN-C (Long Range Navigation) is an electronic system using the differences in the times of arrival of groups of 100 kilohertz radio frequency pulses broadcast by three fixed transmitting stations, to make highly accurate position determinations.

Each LORAN-C triad is composed of a master station and two secondary stations which transmit their pulse groups from known locations in a fixed time sequence. Pulses are transmitted in groups of eight (an extra, ninth, pulse identifies the master). By measuring the difference in the time of arrival of the master and each of the secondary pulses, hyperbolic lines of position over the earth's surface are established. The intersection of these two lines designates the LORAN-C receiver position.

The LORAN-C grid is being expanded on both East and West coasts. This, and the possible mid-continent chain, have made position location potentially available to a larger user group than the maritime community it was designed to serve. New LORAN-C receivers using advanced microprocessor technology are smaller, and lighter than previous systems and are also capable of improved operation in difficult environments.

The Department of Transportation, Transportation Systems Center, is presently conducting experiments in both New York and Vermont to determine the accuracy and repeatability of LORAN-C measurements for both aviation and terrestrial applications. The DOT has developed a mobile LORAN-C laboratory to collect data about

LORAN-C signal performance in mountainous terrain, urban environments and in the presence of man-made and natural interferences, prompted by the need of the user communities. A detailed description of this laboratory and its capabilities appears in Section 4 of this report.

2. OVERVIEW OF THE TESTS

The series of tests were conducted to measure the potential interference to LORAN-C reception. The frequency and amplitude of all noise both continuous wave and burst, in the band from 50 kHz to 150 kHz, was measured, and the modulation, if any, was examined.

In addition, the performance of each LORAN-C receiver was monitored at each test site to determine if proper operation is possible in the vicinity of the interfering sources that might exist at that site.

2.1 MEASUREMENT OBJECTIVES

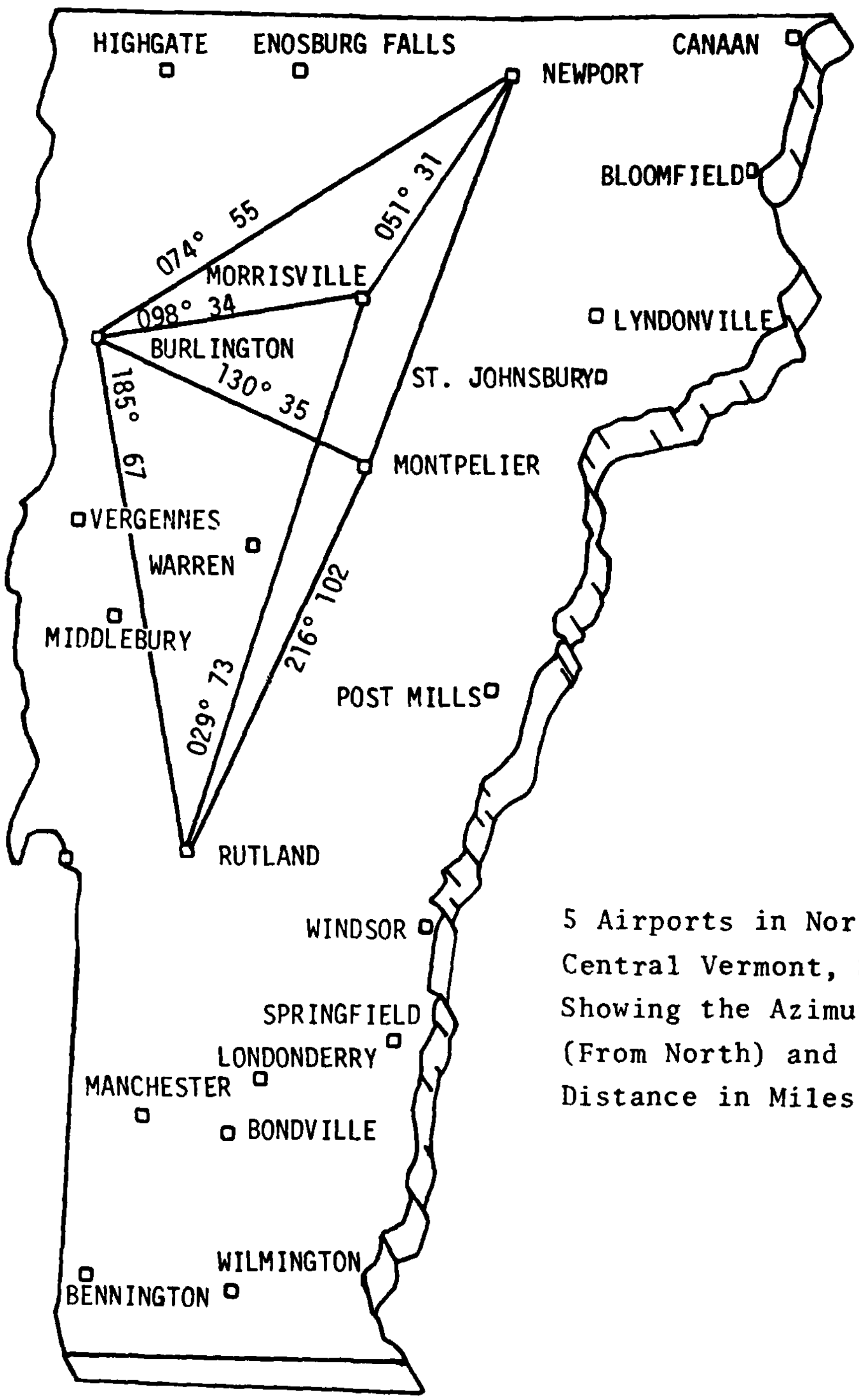
The measurement objectives were to determine:

1. What electromagnetic interference (EMI) is present over the LORAN-C band at each airport?
2. How do typical marine LORAN-C receivers perform in the above environment?
3. Is there a significant difference between the amount of EMI at a small rural airport compared to a large metropolitan one?

2.2 TEST SITES

The test sites chosen were at public-use airports located at Boston, Massachusetts, and at Burlington, and Montpelier, Vermont.

Figure 2-1 is a map of Vermont showing the location of the state's airports. The precise, 1st order land coordinates used at each airport for the measurements were surveyed by the Vermont state government for a program being jointly conducted by DOT, NASA and Vermont. (This program is devoted to the flight test evaluation of LORAN-C suitability for airborne en route navigation operation and non-precision approaches).



5 Airports in North Central Vermont, Showing Showing the Azimuth (From North) and Distance in Miles.

FIGURE 2-1. LOCATION OF VERMONT AIRPORTS

Several sites at each airports were selected in advance, chosen to avoid interference with normal traffic patterns at the airports. Sites were selected both close and far from buildings, terminals, hangars and electronic equipment such as ground surveillance radar, weather sensors, etc in an effort to ensure environments with the most intense sources of interference and noise.

Figure 2-2 shows the layout of runways of Logan International Airport as well as the eight selected sites. The following are reasons for the selection of each particular site.

Logan Airport

Site 1 - Outer perimeter road - Bird Island Flats.
Selected as the southernmost remote location away from all possible sources of interference. Two other compass points are selected below.

Site 2 - In front of the International Terminal.
Selected as a close-in site on the north side.

Site 3 - In front of the North Terminal.
Selected as a close-in site on the east side.

Site 4 - In front of the South Terminal.
Selected as the closest site to the busiest terminal.

Site 5 - At the location of most of the airport's electronics, FAA transmitters, etc.

Site 6 - Outer perimeter road. Easternmost point at the airport; start of Runway 33L.

Site 7 - Outer perimeter road. Northernmost point at the airport start of Runway 22L.

Site 8 - Adjacent to subway in front of the Delta cargo terminal.

Burlington International Airport in Burlington and the Montpelier Airport in Montpelier, Vermont were selected as representative of small rural airports. The Burlington airport is one of the largest in the category of rural airports and is so busy that coordination with the ground control tower was required each time the LORAN-C Mobile Test Facility was moved to a different

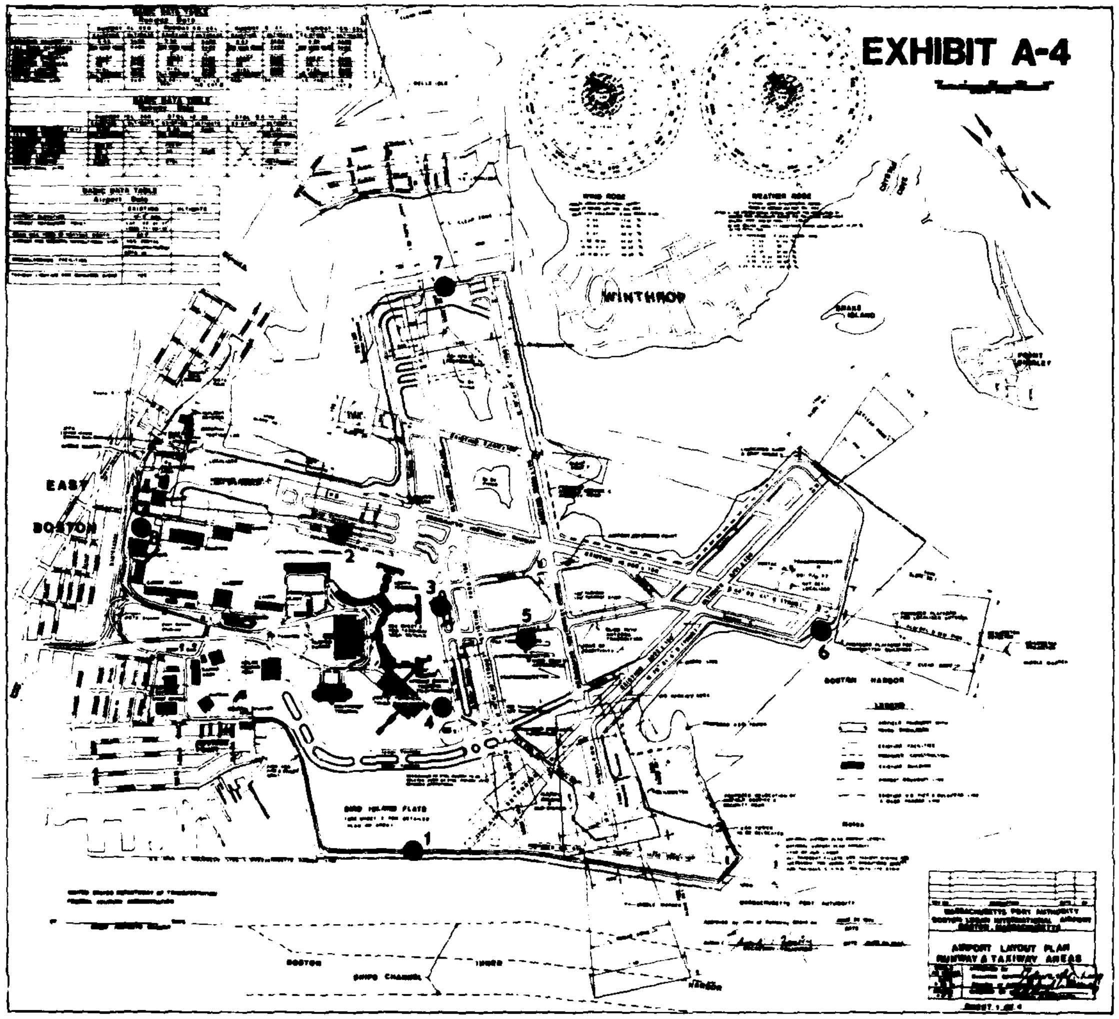


FIGURE 2-2. LOCATION OF SELECTED SITES AT LOGAN AIRPORT

site. It was chosen because of its full complement of radio navigation beacons, surveillance radar and communications electronics. Figure 2-3 shows the location of the selected sites at this airport. The following are the reasons for the selection of the sites at Burlington.

Burlington Airport

Site 1 - 1000 meters north of terminal far from any local interference.

Site 2 - Parking lot adjacent to terminal north side - close to internal interference sources.

Site 3 - 1000 meters south of terminal in front of Air North terminal.

Site 4 - Directly in front of terminal on runway.

Site 5 - 1000 meters from front of terminal on runway.

Site 6 - Adjacent to the airport surveillance radar.

Site 7 - Surveyed site southeast corner of airport.

The Montpelier Airport represents the other extreme in the rural category. Here only one site was selected, directly in front of the terminal since if EMI were to be found, this would be the most probable location.

Montpelier Airport

Site 1 - Surveyed point directly in front of terminal building.

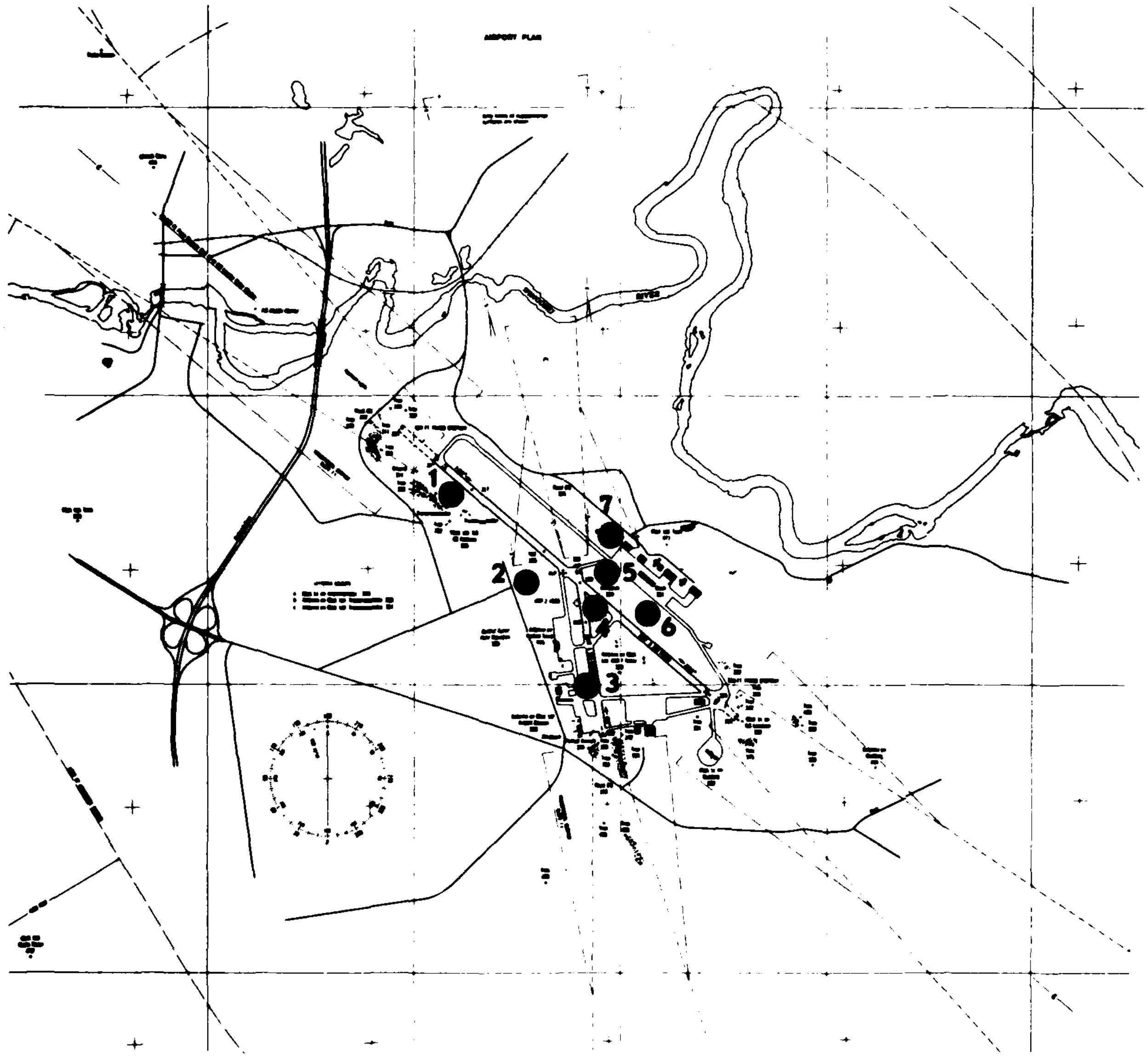


FIGURE 2-3. LOCATION OF SELECTED SITES AT BURLINGTON AIRPORT

3. TEST PROCEDURE

The experimental procedure used to accomplish the test objectives at all sites at all airports was identical, and consisted of two parts.

1. Determine the proper operation of the LORAN-C receivers by measuring the time to acquire and by observing correct tracking and lock of the master and two secondaries.
2. Measure the radiated interference in the LORAN-C spectrum with a calibrated antenna system and spectrum analyzer capable of ±0.1 dB amplitude and ±1.0 Hz frequency accuracy.

3.1 DETAILED TEST PROCEDURE

The LORAN-C Mobile Test Facility (Figure 3-1) was positioned at each site with a random orientation. Since the antenna is a non-directional, vertically polarized, 8 inch blade mounted in the center of the roof of the test van, it was not necessary to point the vehicle in a specific direction.

3.2 RECEIVER TESTS

Receiver tests were performed with and without notch filters.

3.2.1 Receiver Tests Without Adjusting Notch Filters

Upon arrival at each test site, all five LORAN-C receivers shown in Figure 3-2 were switched off and then on to compel re-acquisition of the LORAN-C master and two secondaries at the new test site. The notch filters were tuned to the extreme low end of the receiver pass band. The first measurements were to determine the time required for each receiver to acquire the envelope of each of the two secondaries. These determinations are easily identified by the appearance of the first secondary's "time to acquire" or time delay value, then almost immediately, by the second secondary's time delay value.

FIGURE 3-1. DOT/TSC MOBILE LORAN-C LABORATORY

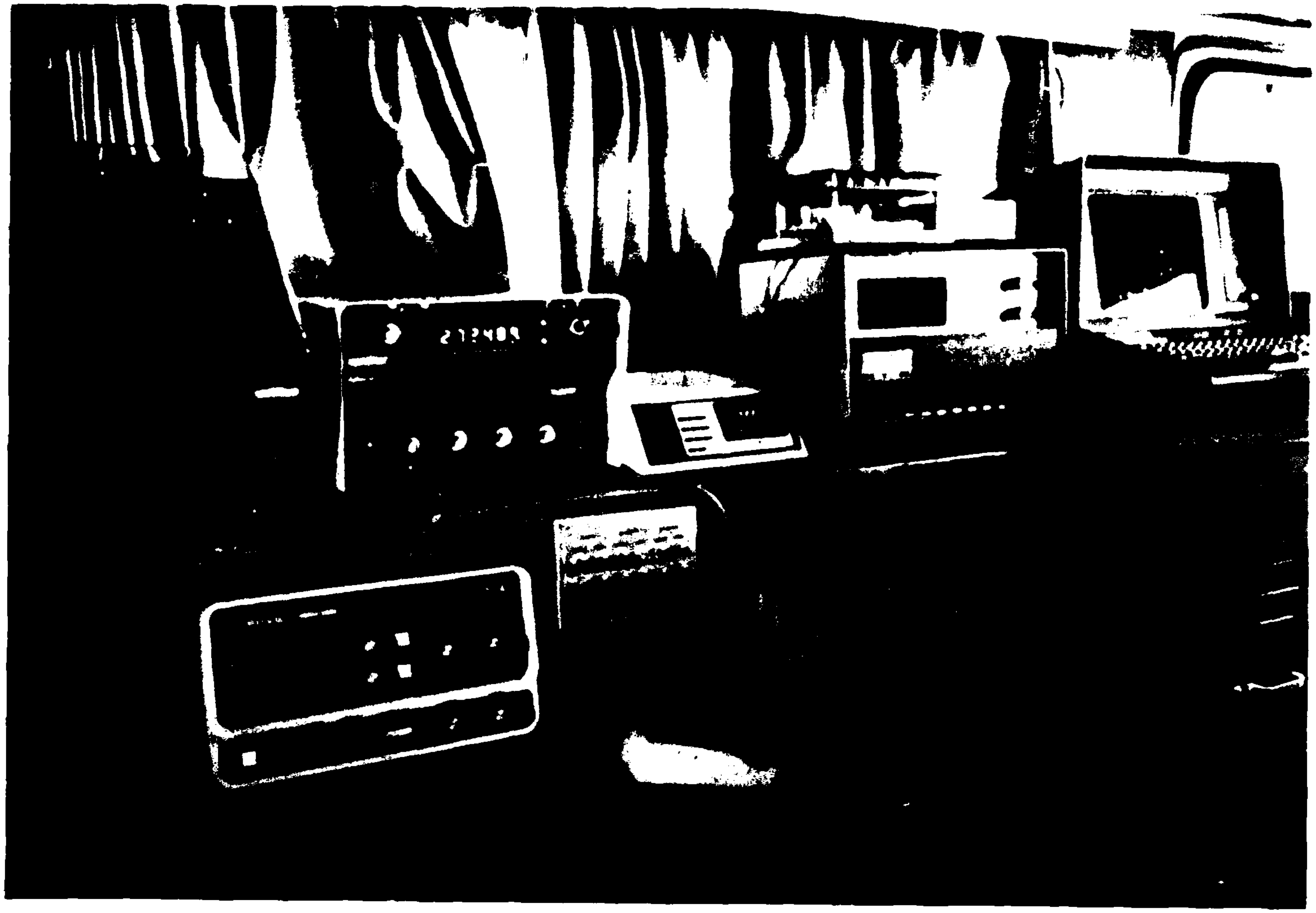


FIGURE 3-2. LORAN-C RECEIVERS IN MOBILE TEST FACILITY

The second measurements were to identify the correct cycle tracking point for each secondary, which is the time to correct the acquisition time reading to the proper value, since the reading will initially be incorrect. This is usually different for each secondary.

These measurements, amounting to four data items, were recorded together with the observed performance of each receiver at each test location for the duration of suceeding interference measurements; a minimum of 1 hour at each test site. All receivers were carefully monitored for:

a. Incidences of loss of lock - indicated by grossly inaccurate time delay readings, or receiver warning indicators.

b. Unusual jitter in the displayed time delay value - greater than 0.3 microseconds indicating burst noise in LORAN-C spectrum on low LORAN-C signal.

c. A constant time delay offset in one or more time delay readings which differs from the readings of the other receivers. This would indicate a synchronous interfering frequency which was either disabling one receiver and not others, or causing a bias in that receiver's cycle identification algorithm. (See Appendix A).

d. A slowly varying time delay reading in one or more receivers. This indicates a near synchronous interference frequency which is beating with a particular LORAN-C line or group of lines in the spectrum.

e. Signal to noise ratio readings from the Micrologic and Texas Instruments receivers.

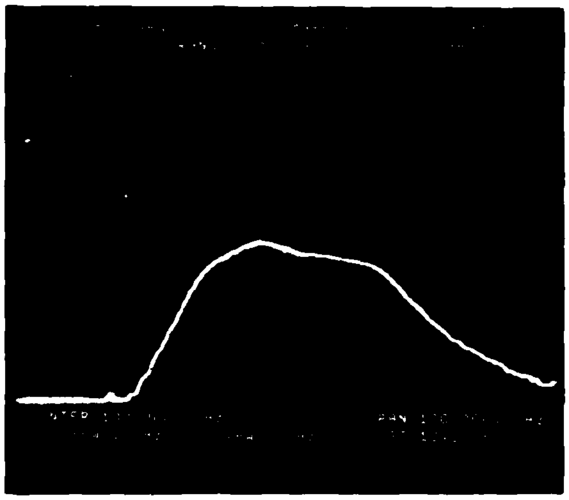
3.2.2 Acquisition Time Measurements After Adjusting the Notch Filters

The notch filters of each receiver were adjusted to have their center reject frequency at 88.0 kHz and at 113.1 kHz; these are the center frequencies of each of the closest predominate sources of continuous wave interference (see Section 5 for a discussion of these sources). The EPSCO and Internav have two filters each; the Micrologic has four, of which only two were used. After these adjustments, the procedure of the preceding section was repeated. The Texas Instruments receiver has internal notch filters which cannot be adjusted in the field. Therefore, data was not taken with the Texas Instruments receiver on 9-26-79 at Burlington survey point #9. Since these notches could not be adjusted, the receiver was assumed to behave as it did during the previous measurements taken on 9-25-79 Burlington Survey Point #10.

The notches were set using the Hewlett-Packard 3585 spectrum analyzer with an internal tracking oscillator. The oscillator signal was fed out to the roof via a co-ax cable and coupled with a short (10 inch) clip lead wrapped loosely (one turn) around the blade antenna. The analyzer was connected to each receiver's front end output, before detection, so that the analyzer displayed the receiver's front end frequency response characteristics. The marker dot was adjusted to 88 kHz then 113.1 kHz and the filters adjusted to notch each of these frequencies. Photographs of the results of the notches before and after adjustment are shown in Figures 3-3 and 3-4. The Teledyne 711 receiver's band pass is shown in Figure 3-3. Even though it was used infrequently during the test, its band pass is shown as a comparison of what can be expected from notch filters.

3.3 CONTINUOUS WAVE INTERFERENCE MEASUREMENTS

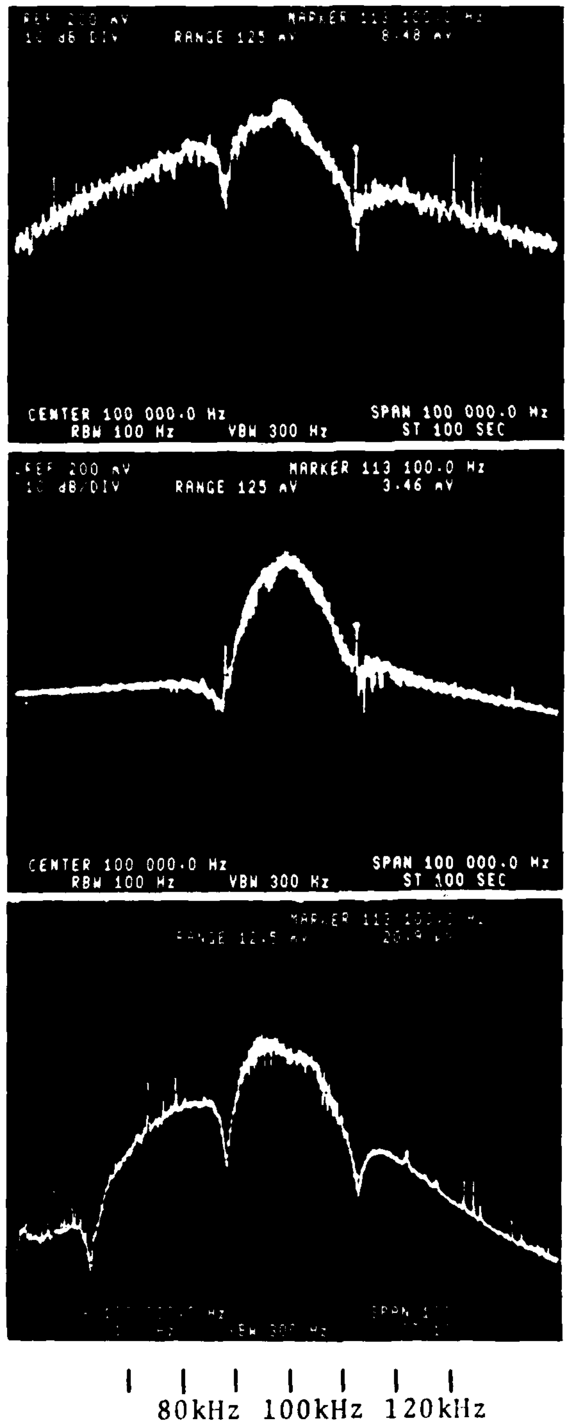
Next, interference measurements were initiated. Using a separate, 50 ohm output tap, the Bayshore UPI-191B antenna amplifier was connected to the 50 ohm input of the Hewlett-Packard 3585 spectrum analyzer. (See Figure 3-5.) The entire LORAN-C frequency spectrum of 50 kHz to 150 kHz was displayed and photographed; then, each 20 kHz portion of the spectrum was examined in turn and photographed.



Frequency response of the receivers front end bandpass filter with both notch filters set full counterclockwise

Frequency response with one filter set at 88 KHZ and the other at 113.1 KHZ

FIGURE 3-3. SETTING THE NOTCH FILTERS OF THE TELEDYNE 711 LORAN-C RECEIVER



EPSCO 4010

INTERVAV 204

MICROLOGIC ML-200

FIGURE 3-4. FREQUENCY RESPONSE OF 3 LORAN-C RECEIVER BAND PASS FILTERS WITH NOTCH FILTERS SET AT 88.0 AND 113.1 KHZ INCLUDING INTERFERENCE AND LORAN-C SIGNAL AT BURLINGTON VT

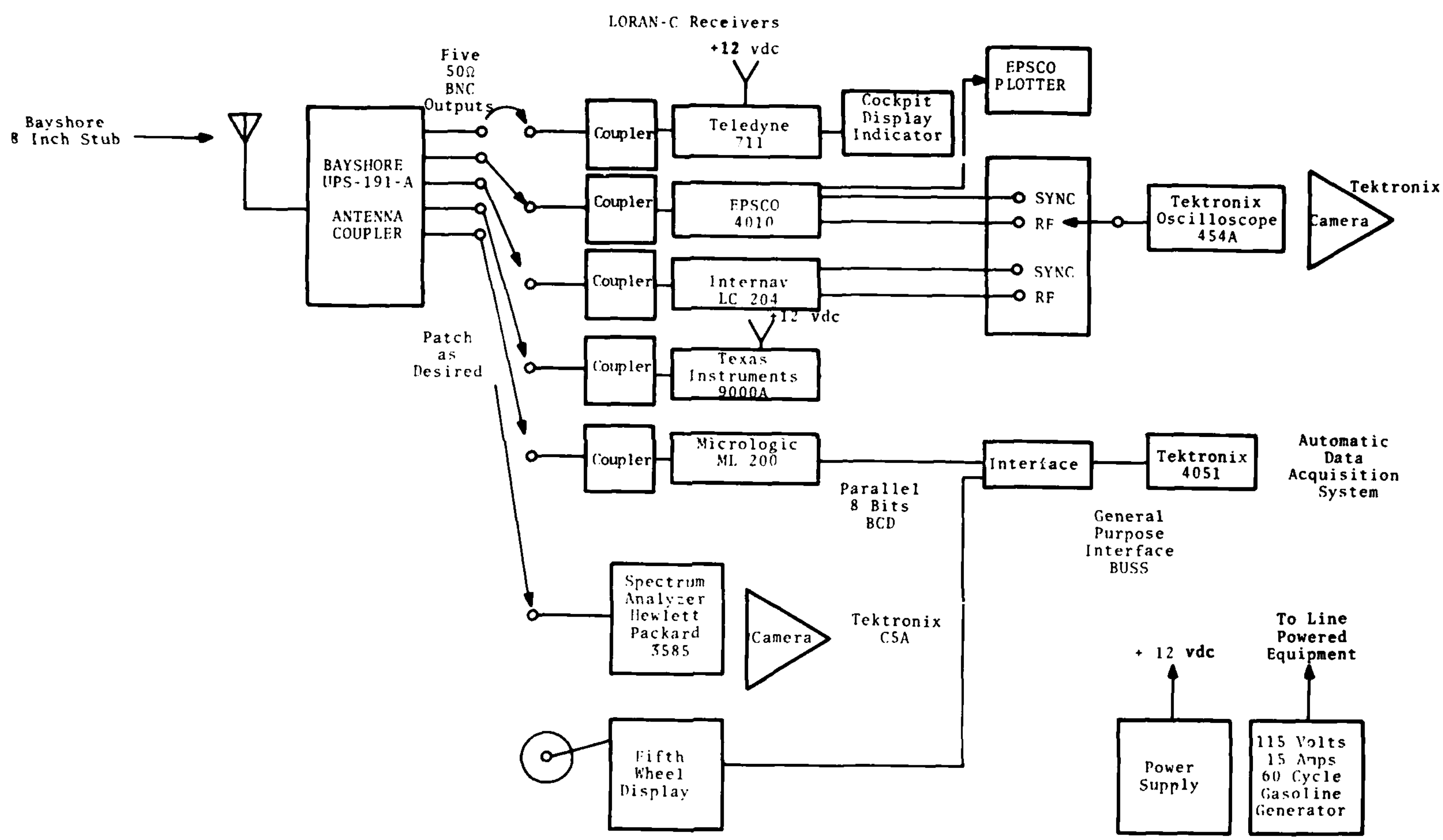


FIGURE 3-5. FUNCTIONAL BLOCK DIAGRAM OF DOT/TSC MOBILE LORAN-C TEST FACILITY

The shape of the LORAN-C pulse is controlled such that 99% of the transmitted energy is contained in the frequency band between 90 and 100 kHz. Bandwidths of available LORAN-C receivers range from relatively narrow bands (18 kHz) to wide bands of 40 kHz. Typical bandwidths are in the region of 24 kHz. For the purpose of this report, "in-band" interference is considered to be interference which is between 85 kHz and 115 kHz and "adjacent band interference" which is from 50 to 85 kHz and from 115 to 150 kHz.

Analysis consisted of examining each of the in-band interference spikes and measuring, in turn, for amplitude, frequency and modulation characteristics. Each spike adjacent to the band but outside of it was also measured for frequency and amplitude.

Only the interference spikes which exceeded -90dB were measured, since smaller ones were judged to be insufficiently large to warrant attention. There were a great many CW transmissions below this level which were difficult to distinguish from noise but the spikes which exceeded -90dB were large and easily identified.

The Hewlett Packard 3585 spectrum analyzer has provisions for measuring frequency and amplitude in a particularly simple way. The marker dot is positioned to the spike of interest and the frequency and amplitude are displayed in the top right corner of the screen accurate to ±0.1 Hz and ±0.1 dB. Each photograph in all figures contained in this report has a marker positioned to one of the spikes. The reader should note for reference the position of the dot, and the corresponding frequency and amplitude of the identified spike. This is useful when judging the photograph for spikes with significant amplitude to warrant detailed measurement.

3.4 TEST FOR SYNCHRONOUS OR NEAR SYNCHRONOUS INTERFERENCE

At each test site, a recording of the time delay values for each secondary was made from the Micrologic receiver at the receiver's update rate, once per 4 seconds, for a total of 30 minutes. This was to determine the presence of near synchronous interference disturbing the receiver's reading which would have evidenced itself by a slowly varying time delay reading - an oscillation about a fixed value of time delay at a frequency equal to the beat frequency of the interference and an adjacent LORAN-C spectral line.

3.5 BURST NOISE AND INTERFERENCE MEASUREMENTS

The above continuous wave (CW) interference measurements were performed with the spectrum analyzer set at extremely slow sweep speeds to reveal all emitters of CW interference, even low power, narrow-band emissions. To determine the burst noise the sweep speed was increased to 1.0 seconds per sweep and the display set to "peak hold" and then monitored for a 10 minute period for unusual transients. These spectrum analyzer settings will capture impulse noise which otherwise would be missed because of the integration time of the anlayzer when set to slow sweep speeds (greater than 100 seconds).

4. DESCRIPTION OF THE MEASUREMENT EQUIPMENT

The mobile LORAN-C laboratory shown in Figure 3-1 contains five different LORAN-C receivers, plotting equipment, automatic data acquisition equipment, a precision odometer and fifth wheel, plus ancillary test equipment. A functional block diagram of this facility is shown in Figure 3-5. A more complete discussion of the data acquisition system is contained in Appendix B. The LORAN-C receivers and Data Acquisition System are shown in Figure 3-2.

5. TEST RESULTS

As described in the procedures, two categories of tests were made to answer the stated test objectives. These were:

a. Receiver acquisition-time measurements

b. Radiated interference measurements in the band 50 to 150 kHz.

Table 5-1 lists all time delay readings at each test site for reference.

5.1 RECEIVER ACQUISITION TIME MEASUREMENTS

Receiver acquisition time is the time required from power on until the receiver has acquired the correct third cycle tracking point of the pulse envelopes from both the master and at least one secondary. Before this occurs, the first time difference reading appears on the front panel display, which normally differs from the correct time delay reading by 50 to 100 microseconds. The receiver's internal signal processing algorithm continues to sample the incoming pulse and refine its estimate of the correct third cycle tracking point until it achieves correct tracking of the LORAN-C pulse. Achieving correct cycle tracking is more difficult than envelope acquisition and inherently requires significantly more time. During this time, interference, either synchronous or near synchronous will have the greatest effect in preventing correct cycle tracking. (See Appendix B.) It is this time that becomes useful when determining the influence of interference. Note, that this applies to continuous wave interference only or interference with a relatively long duty cycle (much greater than 10 seconds) such that it cannot be ignored by the narrow tracking loop bandwidth of the receiver. White noise, or burst type noise,

TABLE 5-1. TIME DIFFERENCE READINGS AT EACH TEST SITE

TEST POINT	MICROLOGIC	EPSCO	INTERNAV	T.I.	711
		BURLINGTON AIRPORT			
1	14225.9	14225.8	14225.7	14225.6	14226.0
	27260.7	27260.5	27260.2	27260.3	27260.5
2	14226.7	14226.5	14226.3	14226.4	14226.7
	27260.3	27260.1	27260.0	27260.0	27260.2
3	14227.5	14227.2	14227.4	14227.3	14227.6
	27259.8	27259.2	27259.1	27259.1	27259.4
4	14226.4	14226.3	14226.1	14226.2	14226.9
	27259.6	27259.1	27258.8	27259.1	27859.4
5	14225.4	14225.3	14225.3	14225.2	14225.4
	27258.6	27258.2	27258.1	27258.1	27258.4
6 SURVEY	14224.3	14224.0	14224.1	14224.1	
POINT	27256.6	27256.2	27256.2	27256.2	
		MONTPELIER, VT			
SURVEY	14068.1	14067.9	14067.8	14067.8	
POINT	2099.8	26994.6	26994.8	26994.6	
		LOGAN AIRPORT			
1	14043.4	14043.6	14043.4	14043.6	
	25872.3	25872.4	25872.4	25872.5	
2	14036.5	14036.3	14036.3	14036.3	
	25874.5	25875.0	25870.6	25870.6	
3	14036.6	14036.4	14036.4	14036.4	
	25870.2	25870.7	25870.6	25870.6	
4	14038.1	14037.9	14037.9	14037.9	
	25870.3	25870.9	25870.9	25870.9	
5	14036.4	14036.2	14036.2	14036.2	
	25867.6	25868.2	25868.1	25868.2	
6	14031.7	14031.6	14031.5	14031.5	
	25857.4	25858.0	25858.0	25858.1	
7	14027.5	14027.4	14027.3	14027.3	
	25867.9	25868.5	25868.3	25868.4	

tends to be averaged out in a typical marine quality receiver due to the hard limiting action of the front end detector. Hence such noise has little effect on the acquisition time.(1)*

From the above, the amount and severity of local continuous wave interference can be estimated by measuring the time to acquire and the time to obtain correct cycle tracking for each receiver.

Table 5-2 gives measurements for the following times (in seconds) to acquire 1) the pulse envelope, 2) the correct time difference A, and 3) the correct time difference B for each receiver at each site. In general, each reading is a simple average of 5 measurements. However, as indicated by an asterisk, some readings are a result of less than 5 measurements. In most cases, this was because the Internav receiver required a good deal of time for each reading. After accumulating 2 or 3 data points, it was felt that sufficient data had been obtained to know that this receiver was having difficulty in achieving lock. Since the point of this measurement is to determine whether or not the receiver experiences difficulty, the measurements can be suspended when a "yes" answer is apparent. In general, if acquisition required longer than 7 minutes (420 seconds) the measurements were stopped. The raw data is given in Appendix D.

Table 5-2 also lists the three times for each of the four receivers used in this test. A fifth receiver, the Teledyne 711, has been mentioned occasionally in this report but since it is being time shared with another TSC program it could not be among the equipments devoted exclusively to these interference measurements.

Table 5-2 shows the Texas Instruments 9000A receiver to be the fastest in achieving correct cycle tracking, although the EPSCO 4010 is almost as fast. The Internav LC-204 requires the longest time for correct cycle tracking. It is out of the scope of this report to comment on the approach each receiver manufacturer has chosen to implement a LORAN-C pulse tracking routine in software.

*Numbers refer to fuller listing in References at end of report.
"Interference Vulnerability of Phase-Lock Loops with Amplitude Limiting and Sampling," Frank, Nick IEEE 69.C31.

TABLE 5-2. RECEIVER TIMES

TEST SITE	EPSCO -4910 ACQUIRE ENVELOPE	EPSCO -4910 CORRECT TDA	EPSCO -4910 CORRECT TDB	TEXAS INST. 9000A ACQUIRE ENVELOPE	TEXAS INST. 9000A CORRECT TDA	TEXAS INST. 9000A SNR	TEXAS INST. 9000A CORRECT TDB	TEXAS INST. 9000A SNR	MICROLOGIC ML200 ACQUIRE ENVELOPE	MICROLOGIC ML200 CORRECT TDA	MICROLOGIC ML200 SNR	MICROLOGIC ML200 CORRECT TDB	INTERNAV 204 SNR	INTERNAV 204 ACQUIRE ENVELOPE	INTERNAV 204 CORRECT TDA	INTERNAV 204 CORRECT TDB
1. 8/27/79 LOGAN SITE 1	14	84	99	35	88	800	93	999	30	198	800	258	1020	12	286	380
2. 8/26/79 PARKING LOT TSC	9	133	133	35	97	750	100	999	28	210	750	203	1020	22	261	380
3. 9/27/79 LOGAN SITE 1	6	155	157	43	84	800	88	999	*2 30	190	800	255	1020	*1 8	405	275
4. 9/27/79 LOGAN SUBWAY	5	120	120	32	77	750	77	999	33	372	850	203	1020	22	>400	305
5. 9/26/79 MONTPELIER VT	8	140	140	45	96	900	93	900	*3 40	210	950	225	1000	10	390	215
6. 9/25/79 BURLINGTON RWY 1	9	134	136	28	76	900	76	900	22	189	900	235	1000	9	416	317
7. 9/25/79 BURLINGTON AIR NORTH	7	123	127	38	80	900	80	900	15	220	850	330	990	*1 8	365	485
8. 9/24/79 PM BURLINGTON SURVEY PT. NO NOTCHES	9	113	127	42	83	900	68	900	30	203	900	217	990	10	396	252
9. 9/26/79 BURLINGTON SURVEY PT. w/Notches #88, 113.1	6	96	96	Notches not adjustable externally					24	190	950	201	990	15	430	245
10. 9/25/79 AM BURLINGTON SURVEY PT. w/Notches	6	121	51	94	94	900	94	900	27	177	950	241	990	*3 8	416	281

NOTE: 1) All times in seconds
2) All readings are 5 sample average except where noted*.

Hence, these measurements were limited to observing the required time to lock and estimating the EMI environment based upon those observations.

As shown in Table 5-2 and plotted in Figure 5-1, the Micrologic ML-200 and Internav LC-204 receivers reflect the increased difficulty in locking to a weaker secondary station, indicated by acquisition time becoming significantly longer. As the signal levels vary with location the acquisition times for these two receivers also vary accordingly. On the other hand, the EPSCO 4010 and Texas Instruments 9000A require almost identical times to acquire each of two secondaries, regardless of the relative strength of each secondary at the reception point.

As shown in Table 5-2 and in Figure 5-2, the signal to noise ratio was positive at all test locations; that is, the LORAN-C pulse envelope was greater than the noise and could be easily distinguished on an oscilloscope. Also, in Figure 5-2 the CW interference is clearly visible. It is manifest as a sine wave base line between LORAN-C pulses. Figure 5-2 is typical of the waveforms received at all locations. At all locations the TI receiver was faster in acquiring correct cycle, (usually, about 50% faster than EPSCO). However, it has much longer envelope acquisition times than any of the other three receivers. The EPSCO has very fast envelope acquisition because it is given the approximate location (the three most significant digits of the time delay) with thumbwheel front panel settings. (The Internav is given one digit.)

The only significant measurement is the time to acquire correct cycle tracking. With this in mind, the times observed for all readings start at the moment of power turn on, such that the envelope acquisition time is included in the correct time to achieve cycle tracking.

A comparison of the acquisition times for the different test sites is shown in Figure 5-1. The acquisition times for each secondary (for both the EPSCO and Texas Instrument receivers) is remarkably similar even though the relative amplitudes of the secondaries vary greatly for each site in Vermont and Boston.

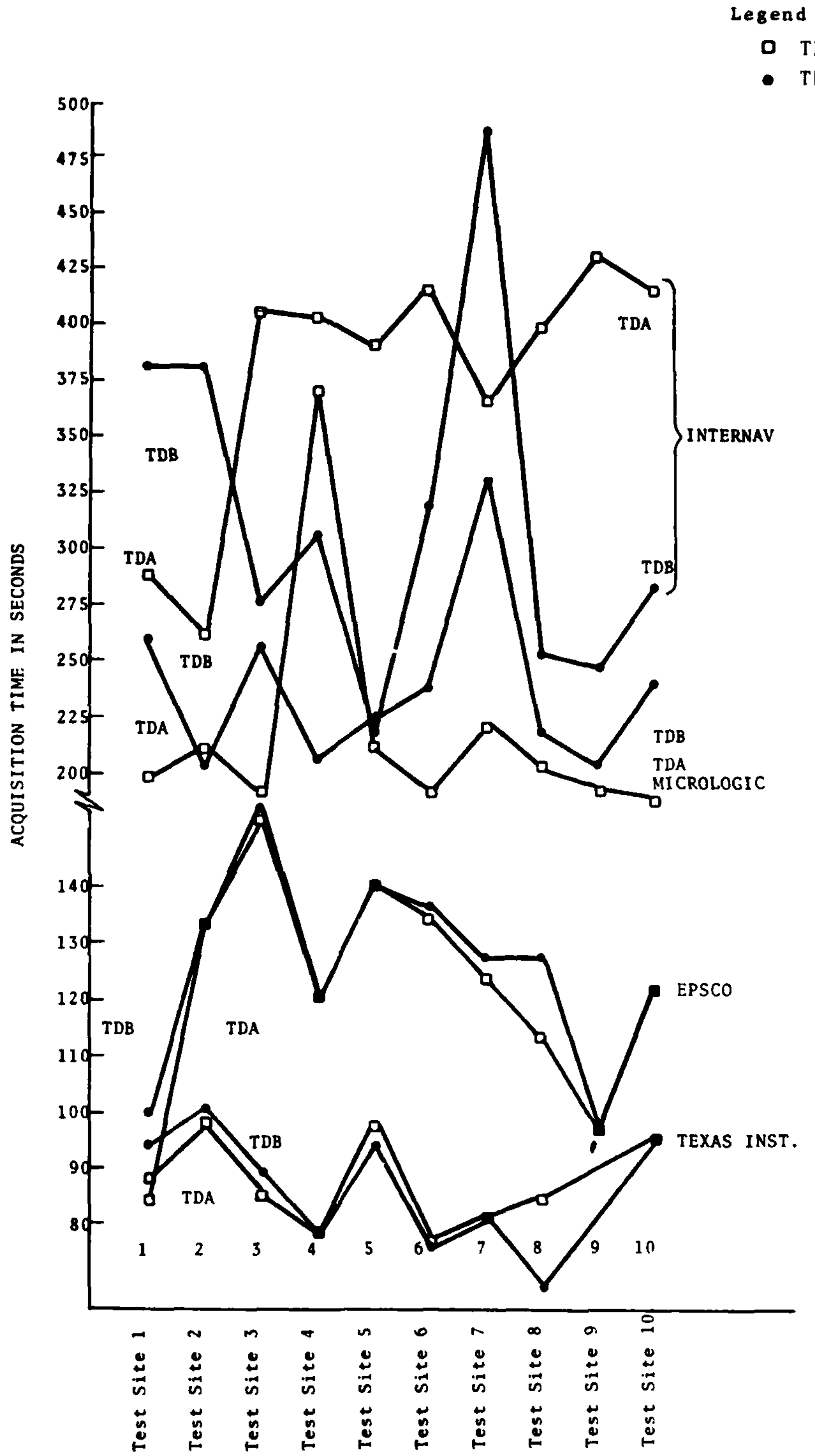
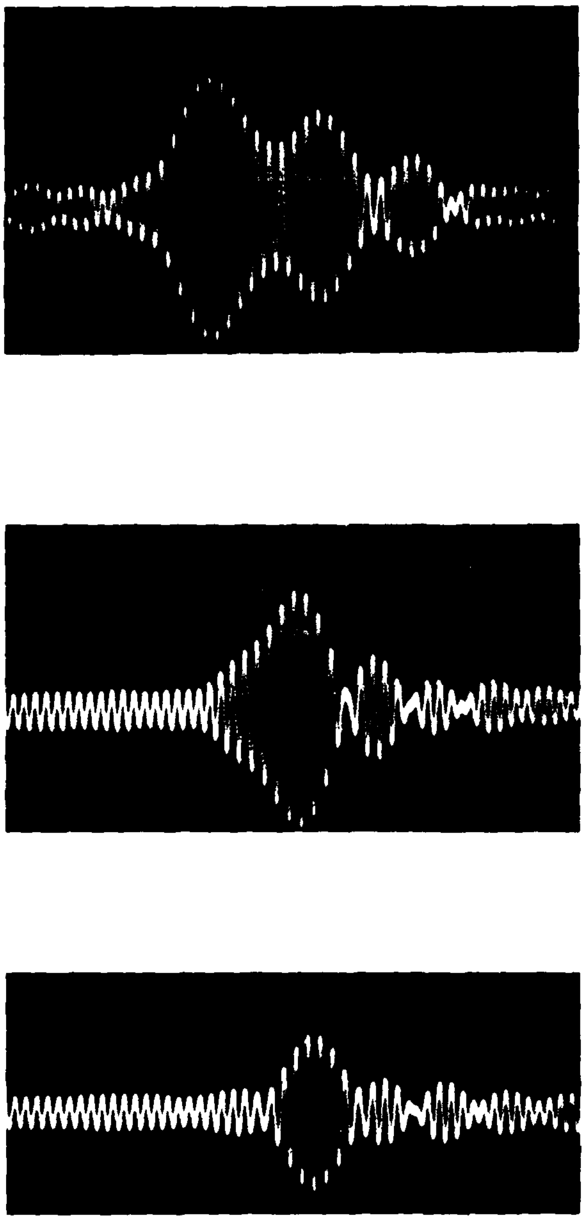


FIGURE 5-1. TIME DIFFERENCE READINGS AT EACH TEST SITE



a) Master station at Seneca N.Y.

0.5 Volts/cm

b) Secondary at Caribou Me.

0.5 Volts/cm

c) Secondary at Nantucket Ma.

0.5 Volts/cm

FIGURE 5-2. THE SHAPE AND RELATIVE AMPLITUDES OF THE LORAN-C PULSES FROM THE NORTHEAST CHAIN (RATE 996) RECEIVED AT THE BURLINGTON VT AIRPORT

The general shape of the two lower sets of curves are similar indicating that the acquisition time of both receivers varies in a similar way as the electrical environment including signal amplitude changes. Visual inspection of the curves reveals a small correlation between the Micrologic and the lower two plots of the EPSCO and TI receivers.

Setting the notch filters of the receivers had little effect on acquisition times. No measurement data indicated the notches improved performance of the receivers. This suggests that the transmissions at 88 and 113.1 kHz have little effect on receiver performance at the Burlington airport.

5.2 RESULTS OF INTERFERENCE MEASUREMENTS

According to the procedure described for detecting near synchronous interference, there was no observed oscillation in the time delay readings. The normal 0.2 microsecond jitter was observed as expected. A sample of this data is contained in Appendix D.

In addition to near-synchronous interference, the possibility exists that an exactly synchronous interfering source could bias the time delay reading by some fixed amount. This was not found at the two survey points where measurements were made. The measured time differences agreed with the values computed for these points to within ±0.5 microseconds.[(2)*] This test could not be performed at Logan because a convenient, known survey point did not exist. A known survey point is needed so that the expected value of the time difference can be calculated for comparison with a measured value at the same point. The location of the survey point must be known to ±500 feet to determine a bias in the time delay reading of 1 microsecond. Greater location accuracy is desirable to enable detection of an even smaller time difference offset.

Table 5-3 lists the time difference readings at each test location and the calculated survey point time delays.

*Results of the Ground Test Evaluation of LORAN-C in the State of Vermont for BLM Approximate Positioning Applications. Material on file at DOT/TSC.

TABLE 5-3. CALCULATED AND MEASURED TIME DIFFERENCE VALUES

	Burlington	Montpelier
Latitude Longitude	44'° 27' 56.28" 73° 08' 47.41"	44'° 12' 10.92" 72° 33' 50.07"
Calculated TDA TDB	14223.79 27256.09	14068.17 26995.42
Texas Inst MEASURED TDA TDB	14224.1 27256.2	14067.8 26994.6
Micrologic TDA TDB	14224.3 27256.6	14068.1 26995.8
EPSCO TDA TDB	14224.0 27256.2	14067.9 26994.6
INTERNAV TDA TDB	14224.1 27256.2	14067.8 26994.8

Calculated LORAN-C Time Difference Values based on:

C = the velocity of propagation = 0.2996411624 Kilometers/microsecond

a = equatorial radius = 6378.135 kilometer

v = index of refraction = 1.0006599

5.3 SPECTRUM PHOTOGRAPHS

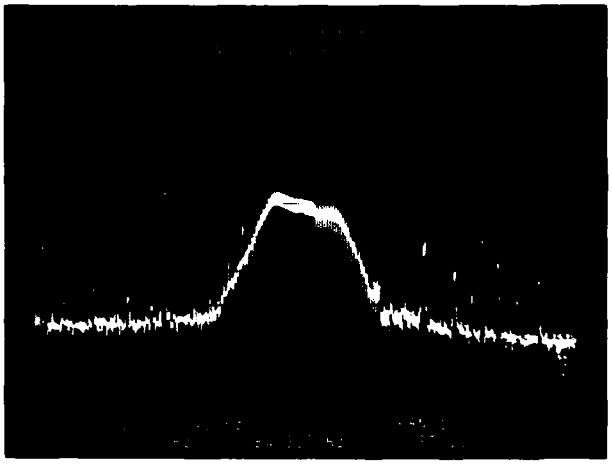
A spectrum scan was made, at each test site, of the LORAN-C and adjacent bands from 50 to 150 kHz. The relative field intensities of all continuous wave interference transmissions in the band were measured, using a Hewlett Packard 3585 spectrum analyzer connected to a separate 50 ohm output on the antenna coupler.

A peak amplitude hold and storage feature incorporated in the analyzer allowed retention of the successive peak amplitudes of spikes and noise from previous sweeps. This is important for capturing transients which may appear at random intervals and not coincide in time with the analyzer's sweep window.

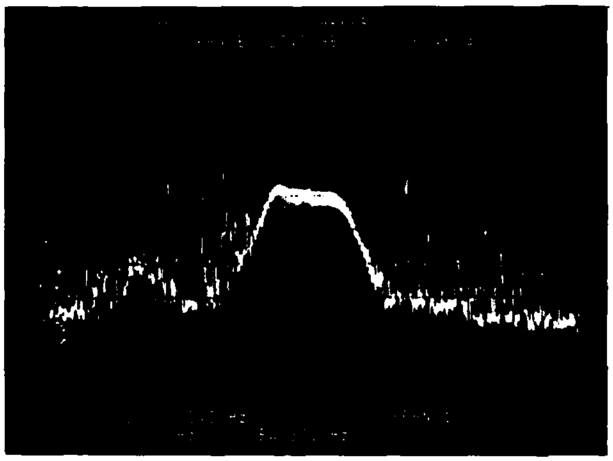
For example, when the noise generator is a subway train the source of noise passes out of range before one sweep time is completed. The presence of train noise is evident only during a forty second portion of the sweep, as shown in Figure 5-3.

This feature was used to advantage in displaying the noise transient produced by a defective air to ground radio used in the test van. In order to cross runways, permission from the ground controller tower was required. A Collins VHF-20 radio was used for the contact. While this radio was monitoring the ground control frequency, a number of noise pulses appeared on the analyzer's display which coincided with voice modulation coming from the radio. It was discovered that the voice amplifier in the radio was clipping the voice waveform and producing harmonics spread out across the entire 50 to 150 kHz band. Figure 5-4 shows an analyzer display photographed at the Burlington, Vt. airport.

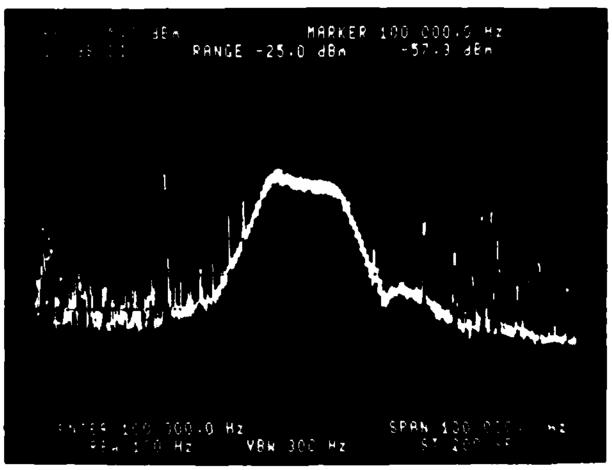
After accumulating two successive sweeps at Boston's Logan airport, the spectral lines due to noise become so dense they raised the base line level by 20 dB. An example of this is shown in Figure 5-5. The radio was replaced and the noise was cleaned up entirely, but the experience highlights the necessity for EMI reduction capability in cockpit equipment, especially for unlikely sources and receptors such as a radio receiver's audio section and a LORAN-C receiver.



a) No traffic passing measurement site

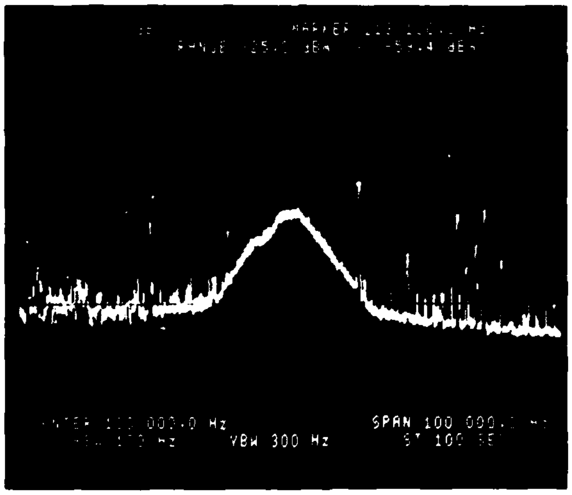


b) Passing train causes interference and noise for the first forty seconds of the 100 second sweep time.

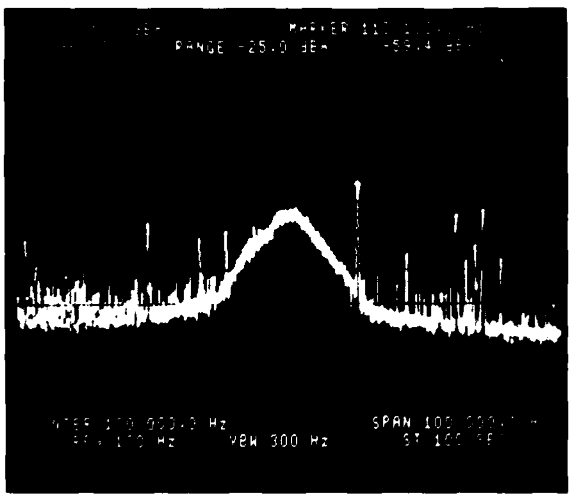


c) Passing train causes interference and noise for first forty seconds of the 200 second sweep.

FIGURE 5-3. LORAN-C SPECTRUM ADJACENT TO A BOSTON SUBWAY LINE



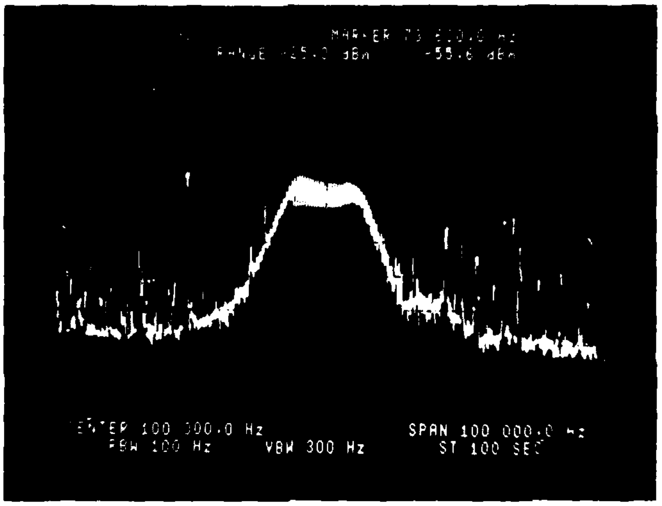
a) No internal interference



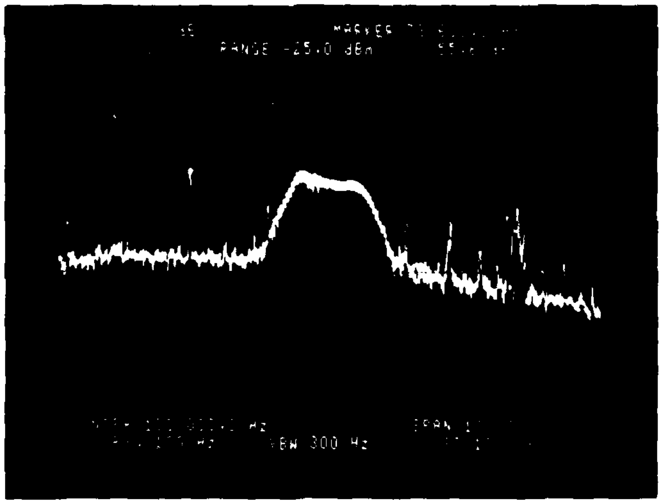
b) Aircraft radio generating interference.

Note the increase of transient spectral lines interspaced between existing external interference spikes

FIGURE 5-4. LORAN-C SPECTRUM WITH AND WITHOUT OPERATING A DEFECTIVE AIRCRAFT TO GROUND RADIO IN THE RECEIVER MODE ONLY



a) LORAN-C spectrum at Logan Airport, Boston Ma. without internal interference



b) Increase in broad band noise caused by aircraft to ground receiver brings up base line by 20 dB besides adding transient spikes

FIGURE 5-5. COMPARISON OF NOISE AND INTERFERENCE IN THE LORAN-C SPECTRUM WITH THE ADDITION OF AN AIRCRAFT RADIO IN THE RECEIVE MODE ONLY INTERNAL TO THE MEASUREMENT VAN

A complete listing of the amplitude of every spike above -90dB (relative) at each test site is given in Table 5-4. This table lists signals due to transmitters in the 70 to 130 kHz band during the measurement period. Most of these transmissions are from Decca stations in Canada. Transmissions observed but not identified during the measurement period are also listed. The listing gives the amplitude in dB below the reference level of -25dBw. That is, the top horizontal graticule line is equal to 25dB below 1 watt into 50 ohms and all amplitudes listed in dB below that reference. Use of this standard reference level makes the photographs in all spectrum figures of this report consistent. The amplitude can be converted to field intensity, using the procedure described in Appendix C, by adding 153 dB. This converts the reading to dB above one microvolt per meter.

The spectrum photographs at the airports, Figures 5-6 through 5-9, indicate that the interference spikes appear consistently at all locations, although they vary in amplitude. The two closest to the LORAN-C spectrum are the Navy transmission at 88 kHz from Annapolis Md. and a Canadian communication transmission at 113.1 kHz from Ottawa, Canada. These two originate from opposite directions such that closer to Boston, 88 kHz increases in amplitude, and toward Burlington VT, 113.1 kHz increases. This is clearly depicted in Figure 5-8.

Another significant spike is the 73.6 kHz communication transmission from Nova Scotia which appears at all locations, along with five others; 131.4 Ontario, 133.1 Halifax, 134.8 Annapolis Md., 136.2 unknown, and 139.5 Newport R.I. These are easily identified at all locations and only the amplitude varies with location. The LORAN-C user must be aware of a potentially severe interference source as he approaches the location of these transmitters, especially the transmissions at 88 and 113.1 kHz. It is important to set the notch filters to each predominant frequency when operating in the Northeast region. All other significant transmissions are sufficiently removed in frequency from the LORAN-C spectrum to suffer attentuation from the receivers' front end bandpass filters.

TABLE 5-4. AMPLITUDE OF ALL SPIKES ABOVE -90dB AT EACH AIRPORT IN THE FREQUENCY RANGE 70 TO 140 kHz

FREQUENCY kHz	LOCATION IF KNOWN	POWER KW	USE	BURLINGTON SURVEY PT.	MONTPELIER SURVEY PT.	LOGAN TEST SITE 1
70.387	NEWFOUNDLAND	1.2	DECCA	-97		
71.142	ECUM SECUM NOVA SCOTIA	2.7	DECCA		-89	
71.438	CLARKE QUEBEC	1.2	DECCA	-91		
73.6	NOVA SCOTIA	250	COMM	-74.4	-61	-56
76.8						-82
77.5						-71
79.250				-95		-64
85.370	CHESTER NOVA SCOTIA	1.2	DECCA	-88	-90	-78
85.725	PORT MENIER QUEBEC		DECCA	-89.9		
88.0	ANNAPOLIS MD	50	COMM	-75	-71	-63
LORAN-C PEAK				-65	-71	-54
113.1	OTTAWA	3	COMM	-60	-70	-77
113.827	ALMA NOVA SCOTIA	1.2	DECCA			-80
114.3	SHIPPEGAN QUEBEC	1.2	DECCA	-90	-91	-82
115.3	HALIFAX	250	COMM			
117.157	QUEBEC	1.2	DECCA	-90		-78
119.85	NORFOLK	2				
112.3	ONTARIO	3	COMM	-81	-84	-70
122.5	HALIFAX	15	COMM		-93	-69
128.558	NATASHQUAN QUEBEC	1.2	DECCA		-95	-79
131.4				-70	-73	-86
134.8				-80	-80	-67
136.2				-67	-73	-76

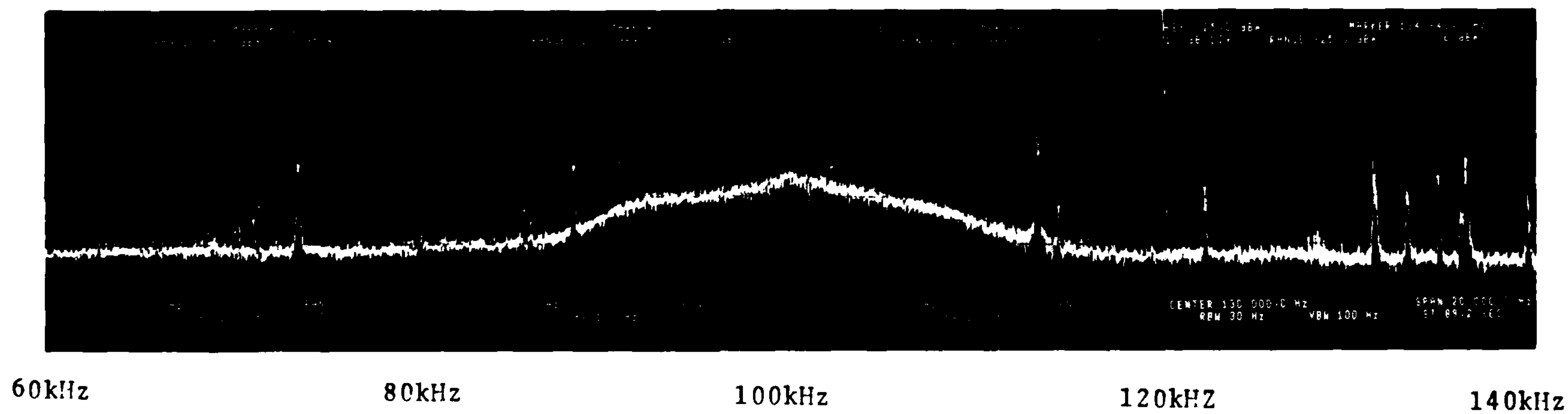


FIGURE 5-6. LORAN-C SPECTRUM AT THE BURLINGTON VT AIRPORT FROM 60 KHZ SHOWING AN EXPANDED SWEEP DETAIL OF THE CONTINUOUS WAVE TRANSMISSIONS

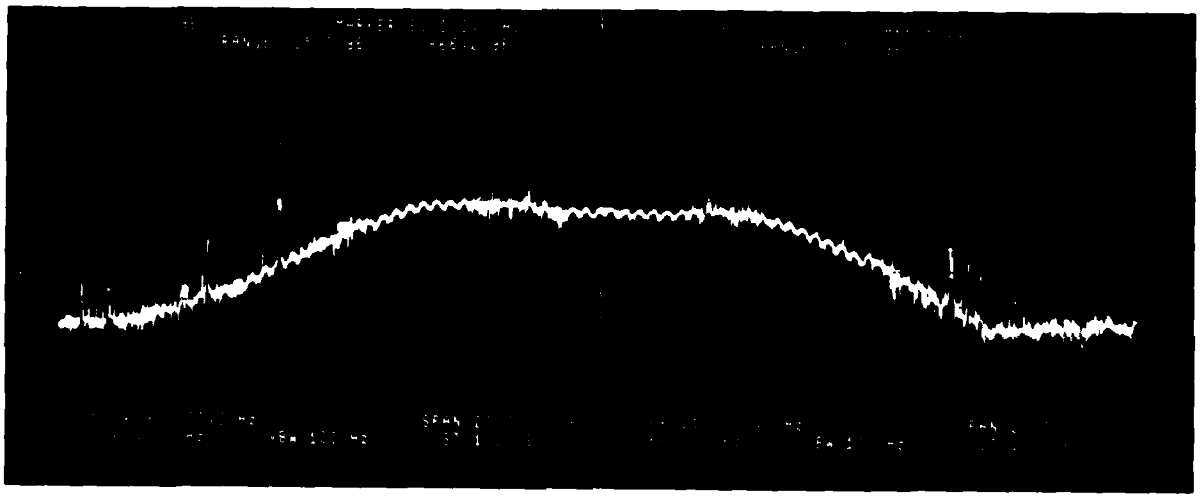
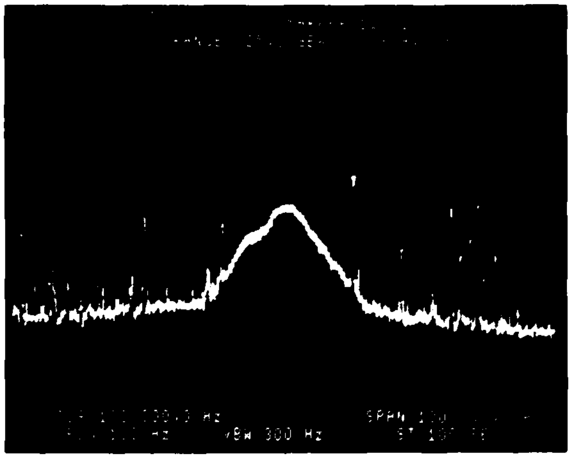
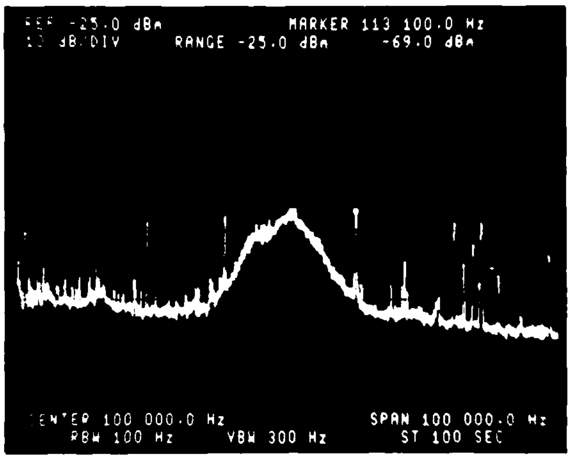


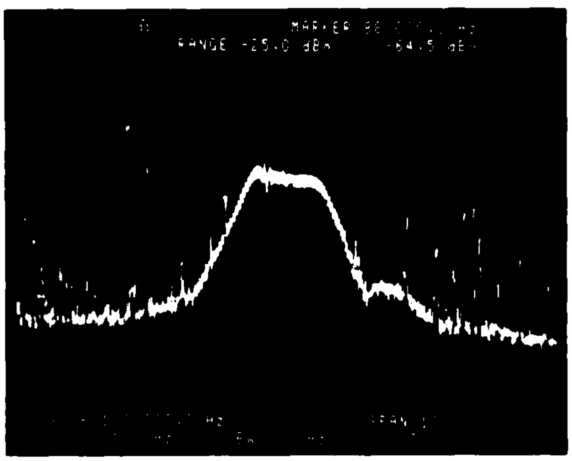
FIGURE 5-7. THE LORAN-C SPECTRUM AT LOGAN AIRPORT IN BOSTON MA
80 KHZ to 120 KHZ



Burlington Vt. Airport.
Note large amplitude of
the 113.1 kHz Decca spike
from Canada

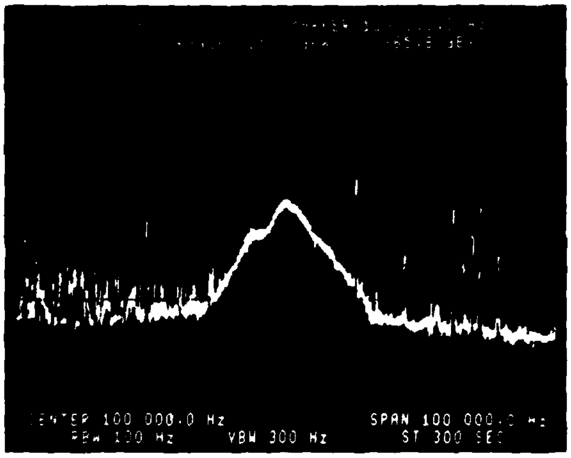


Montpelier Vt. Airport
note 10 db reduction in
113.1 kHz and 4 db increase
in 88 kHz transmissions

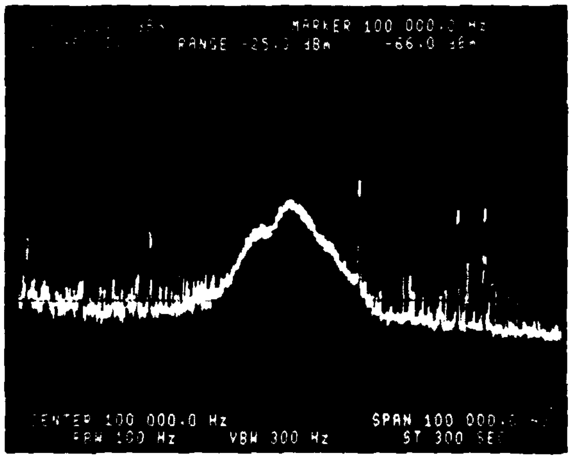


Logan Airport, Boston Ma.
note the increase in
LORAN-C signal strength
due to proximity of the
Nantucket secondary

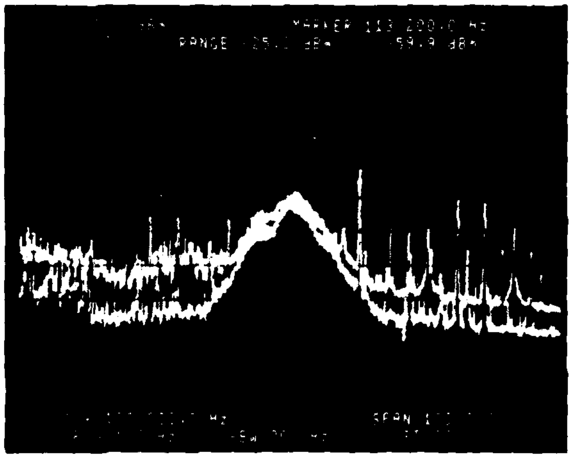
FIGURE 5-8. SPECTRUM PHOTOGRAPHS OF THE LORAN-C BAND 50 KHZ TO 150 KHZ AT EACH OF THE THREE AIRPORTS WHERE MEASUREMENTS WERE MADE



At NOON on 9-24-79



At 8 PM on 9-24-79



Upper trace - Terminal parking area
Lower Trace - Survey point

FIGURE 5-9. LORAN-C SPECTRUM AT THE BURLINGTON VT AIRPORT COMPARING DAY AND NIGHT INTERFERENCE LEVELS AND OPEN AREA (SURVEY POINT) VS TERMINAL AREA INTERFERENCE

Figure 3-4 is the frequency response of three of the receivers. It is clear that frequencies outside of the 70 to 130 kHz range are attenuated by at least 40 dB.

Table 5-4 is a listing of the amplitude of all spikes above -90dB. Approximately ten CW transmissions in the 70 to 130 kHz band are found at all locations.

5.3.1 Burlington Vt. Airport

The interference measured from the airport services or from any of the electronic equipment used for navigation, communication or weather sensing, revealed no identifiable source which could cause a disturbance to the LORAN-C receiver. When the test van was parked outside the Air North Terminal at the Burlington, Vt. airport a 10 dB increase in the base line noise level was noticed. (See Figure 5-9.) This is white noise in the LORAN-C band but it's still 20 dB lower than the LORAN-C signal itself. Marine quality receivers with hard limiters will perform slightly better with some additive white noise,[(10)*] and at this location the LORAN-C signal still has a positive signal to noise ratio. As the acquisition time measurements show, there are no performance difficulties anywhere on the field of the airport including adjacent to the Air North Terminal. However, the Internav and EPSCO receivers do show a significant increase in time to acquire the weaker TDB (Nantucket) secondary. Note, in Figure 5-9, the LORAN-C spectrum differences between 12 noon and 8 p.m. on the same day. Some transmissions have ceased while others have been initiated.

5.3.2 Logan Airport

At a major airport, Logan, in Boston, Ma., interference measurements were made at eight sites along the perimeter as well as close to terminals, hangers and electronic equipment. An eighth site, between the subway and the Delta cargo terminal, was

*Hard Limiting Applied to Loran-C, P.Van Der Wal, IEE AES-14, July 1978.

selected as potentially having the poorest reception at the airport. The bottom trace of Figure 5-8 is the spectrum at Site 1. Note the much stronger LORAN-C signal due to the proximity of the LORAN-C transmitter at Nantucket Ma. Here again, the only significant interference sources were outside the perimeter of the airport, none was measured at the airport itself and none could be distinguished anywhere on the field. Figure 5-7 is an expanded spectrum photograph taken at Logan Airport Site 1.

The subway site was a slightly diminshed reception area but not at all poor. When the subway train passed a great deal of interference was generated which is clearly visible in Figure 5-3. All receivers experienced difficulty in either acquisition or tracking when operated in that environment continuously. But, the receivers easily tolerated the electrical noise of a passing train during the 40 seconds it took from start of impulse noise, when a train was in view, to the time it traveled to the limit of view.

For this program of measurements the transmitted frequency of CW transmissions was determined to be $\pm$ 100 Hz. To be synchronous (or near-synchronous) the carrier must be stable to one part in 10^5 and be less than 1 Hz away from a LORAN-C spectrum component. Because of the difficulty in measuring frequency to determine synchronism, the performance only of the receivers was observed. During this measurement program, no effects of synchronous interference from either power lines or adjacent channel transmissions were noticed in the performance of the LORAN-C receivers.

6. SUMMARY AND CONCLUSIONS

The data accumulated by the measurements described in this report show that no major sources of interference to LORAN-C reception exist on the fields of either small or large airports where tests were conducted. In fact, at Logan, in Boston, where noise and interference would be expected from the adjacent city, the electrical environment in the LORAN-C band is surprisingly free of interference. It is concluded that the broad band electrical noise found in city areas[(3)*] is short range and does not extend to the airports at Boston, Burlington and Montpelier.

Continuous wave transmitters intended for various communications and navigation purposes which are not located at the airport, are potential sources of interference and are measureable at the above three airports. The Navy transmission at 88 KHz from Annapolis, Md. is easily measured at Logan and even as far North as Burlington Vt. however it did not interfere with the proper acquisition of operation of LORAN-C equipment. This was also true of the Decca transmission at 113.1 kHz from Ottawa Canada, strongest at Burlington Vt. and down 30 dB at Logan.

The airport electronic navigation and communication equipment does not produce significant interference to the LORAN-C receivers, which had no trouble acquiring or tracking the LORAN-C pulse at any location.

Based on the measurements of time to achieve correct cycle tracking, and on the signal-to-noise ratio (which is diminished by the presence of CW interference), there appears to be a measureable amount of interference but not a sufficient amount to prevent operational reception of LORAN-C at any of the test sites.

*Urban and Suburban Radio Noise and RFI Environment Encountered by Vehicular LORAN-C Systems - W.R. Vincent, System Control Inc., Report No. 6893/6894-230579.

The longer acquisition times required by the Internav LC-204 are not typical of marine quality receivers as proven by the Texas Instruments and EPSCO receivers, and is probably due to a combination of the "correct-cycle-identification" software used, and interference.

It is concluded that the Micrologic and Internav receivers do not behave in a fashion similar to the EPSCO and Texas Instruments receivers, and that good performance (acquisition time and tracking) is a function of manufacturer and model. The airport environment at Boston and Burlington has caused a design weakness to surface in some recievers but others are able to perform well.

These measurements indicate that LORAN-C performance for the 3 airports tested, was reliable on the surface and in the terminal area without interference causing misleading or wrong time delay readings.

The most important factor is whether the large easily identified transmissions ever become near-synchronous with any of the LORAN-C spectral components. It has been shown in a previous report[(4)*] that synchronous or near-synchronous interference (even out of band 85 kHz) has a marked effect on the performance of LORAN-C receivers. There is a cooperation to prevent the mutual interference between LORAN-C and DECCA transmissions,[(5)**] but, if some other unnoticed, narrowband CW transmitter began broadcasting at a near-synchronous frequency outside the LORAN-C band, receivers in the vicinity would surely be affected (See Appendix F.)

A new look at the EMI compatability among cockpit equipments is suggested by the interference discovered during these measurements. The air to ground radio and other communication equipment are not normally considered sources of interference. However, evidence disclosed in this report proves interference is possible even from these unlikely sources.

*Report No. DOT-TSC-RSPA-79-8, "The Effects of Primary Power Transmission Lines on the Performance of LORAN-C Receivers."
**Text - LORAN-C Engineering Course, U.S. Coast Guard.

APPENDIX A

SYNCHRONOUS AND NEAR-SYNCHRONOUS INTERFERENCE

INTRODUCTION

The LORAN-C signal is made up of many different frequency components and the amplitude and phase of each component is important to the construction of a proper LORAN-C pulse. Undesirable signals which are not part of the LORAN-C spectrum, but which fall within the bandwidth of the LORAN-C signal must be regarded as interference. Such interference can disturb the pulse shape and cause LORAN-C receivers to give erroneous tracking information. Signals of a continuous nature are particularly troublesmome. These may arise from adjacent channel signals like Decca, or FSK transmissions such as the Navy transmissions at Annapolis, Md. on 88 kHz.

If the frequency of the interfering signal falls exactly on a frequency which is present in the LORAN-C fine-line spectrum, it is called synchronous interference. If the frequency of the interfering signal is nearly, but not exactly equal to a LORAN-C component, the interference is termed near-synchronous. Near-synchronous interference is a signal whose frequency does not coincide with a LORAN-C spectral line but is so close as to be less than the bandwidth of the receiver's tracking loop away from the actual LORAN-C spectral component.

A-1 Basic LORAN-C Signal Structure

All LORAN-C transmitters transmit on a common frequency of 100 kHz. Transmissions from various LORAN-C transmitters are time multiplexed, with each transmitter sending out a burst of pulses and then remaining silent for a predetermined period. A typical transmission sequence is shown in Figure A-1. First, the Master station transmits a burst of 8 pulses, separated by 1 msec time intervals, and followed 2 msec later by a 9th pulse (the 9th pulse is used for control and identification purposes). Following transmission by the Master station, the associated Secondary stations

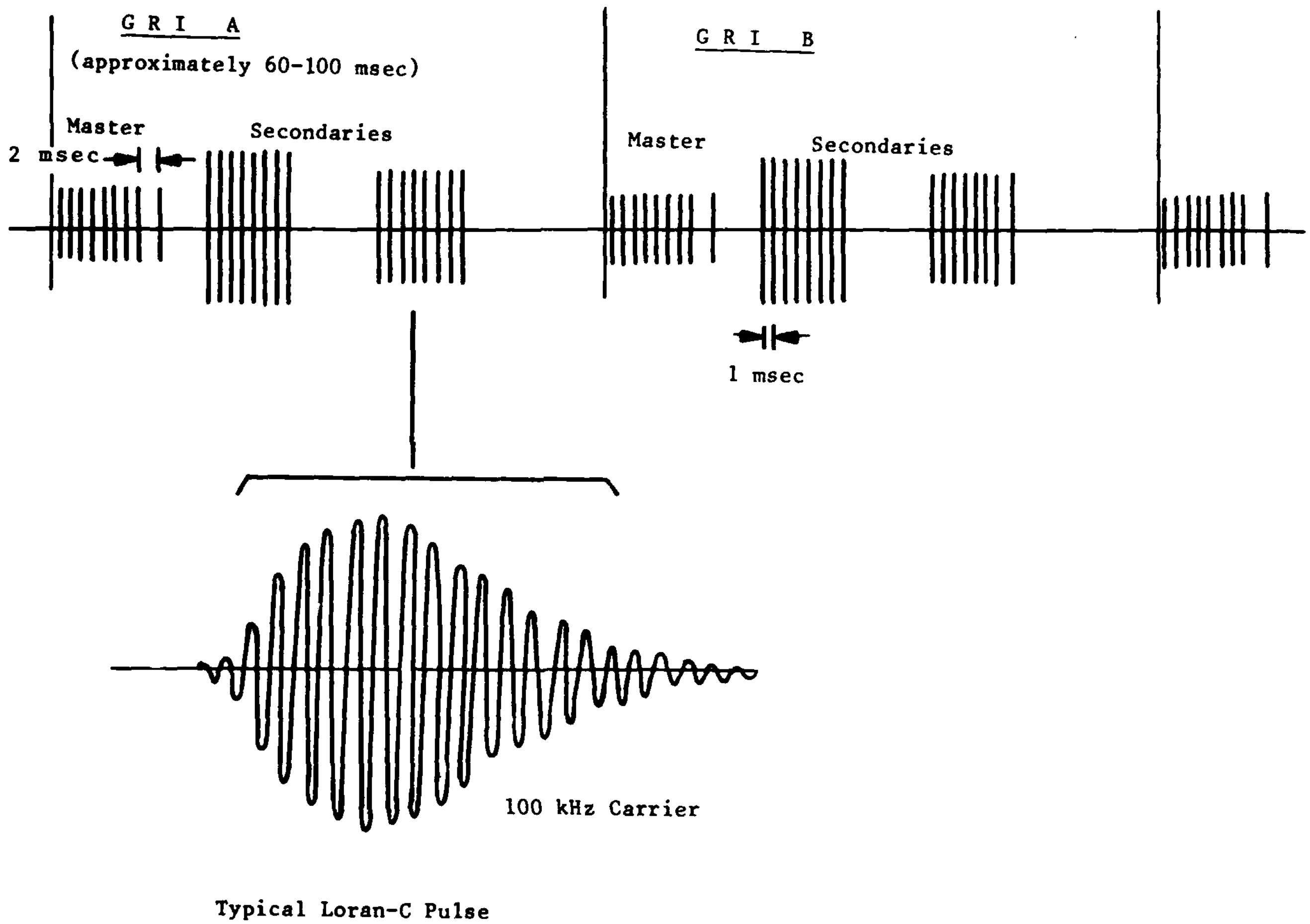


FIGURE A-1. LORAN-C SIGNAL STRUCTURE

transmit bursts of 8 pulses, separated by 1 msec. As shown in the expanded view, each pulse consists of a burst of 100 kHz carrier. The shape of the pulses is carefully controlled to limit the energy of the transitted signal to the frequency spectrum between 90 and 110 kHz, and to provide an amplitude phase relationship during the leading edge of the pulse, which will permit identification of a given cycle inside the pulse.

The transmission from each station is repeated periodically at a time interval known as the Group Repetition Interval (GRI). Typically, the GRI ranges from 60 to 100 msec, although shorter intervals are permitted.

To identify the Master transmitter and to provide a degree of immunity against skywave interference, the LORAN-C pulses are phase coded. This is accomplished by shifting the phase of the pulse either 0 or π radians. A unique phase code is assigned to the Master station to assist in receiver acquisition, while the secondary stations share the same phase code. (Each Secondary station is identified by its time delay from the Master station transmission.) The assigned phase codes repeat at intervals of 2 GRI. Identifying alternate GRIs as A and B, and further representing phase shifts 0 and π radians by the symbols + and - respectively, the assigned phase codes are:

	STATION	
GRI	Master	Secondary
A	++--+-+-+	+++++--+
B	+--+++++-	+-+-++--

An examination of the assigned phase code shows that the LORAN-C chain transmission seuqence repeats at intervals of twice the GRI, and further that the phase code is not balanced due to the excess of + pulses.

A-2 LORAN-C Pulse Time of Arrival Measurement and Interference

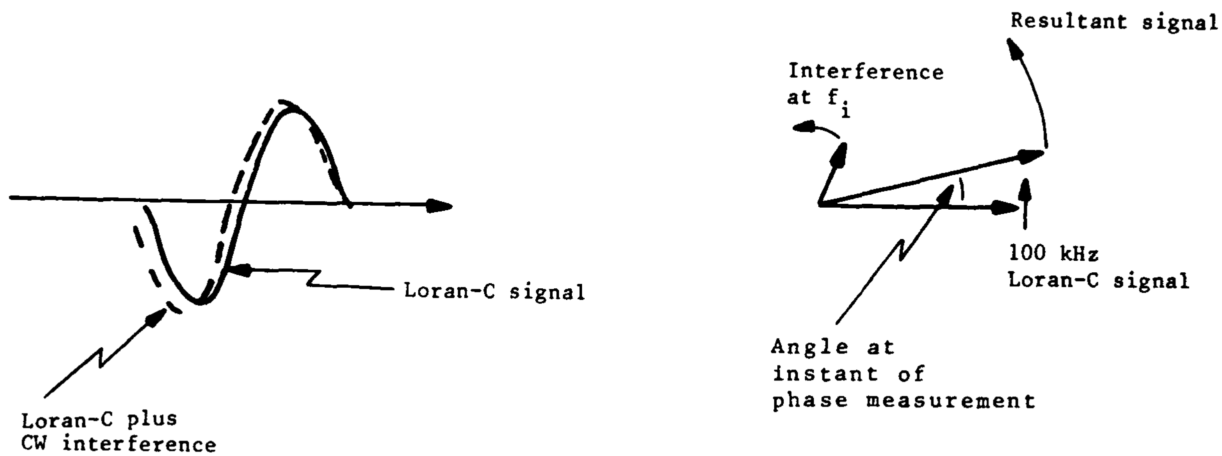
Using signals from the LORAN-C Navigation System, position is determined by comparing the time difference between the arrival of the pulses from the Master transmitter and the pulses from each selected Secondary transmitter. The time of arrival of the LORAN-C pulse is referenced to the third cycle zero crossing at the leading edge of the pulse, with the time of arrival of the bursts of pulses referenced to the first pulse using the known 1 msec spacing between pulses. (The additional pulses are used to improve the quality of measurement.) The effect of CW interference may be viewed as the vector addition of the instantaneous CW frequency to the frequency of the selected LORAN-C pulse cycle. This relationship is shown in Figure A-2.

As the frequency of the CW interference beats against the 100 kHz LORAN-C pulse frequency, the zero crossing of the LORAN-C pulse is caused to oscillate about its true position.

The time difference information used to determine position is obtained by subtracting the time of arrival measurement for the Master station from a similar time of arrival measurement for a Secondary station. Prior to subtraction, the individual time of arrival measurements are averaged over successive GRIs to reduce the effect of noise and interference. For example, if a GRI of .0993 seconds is considered (this corresponds to the LORAN-C chain with rate 9930), and a receiver integration time of approximately 10 seconds is assumed, each time difference measurement will be the average of 100 LORAN-C GRIs with each interval comprised of eight individual pulse measurements for the Master and Secondary stations (an 800 pulse average for each station).

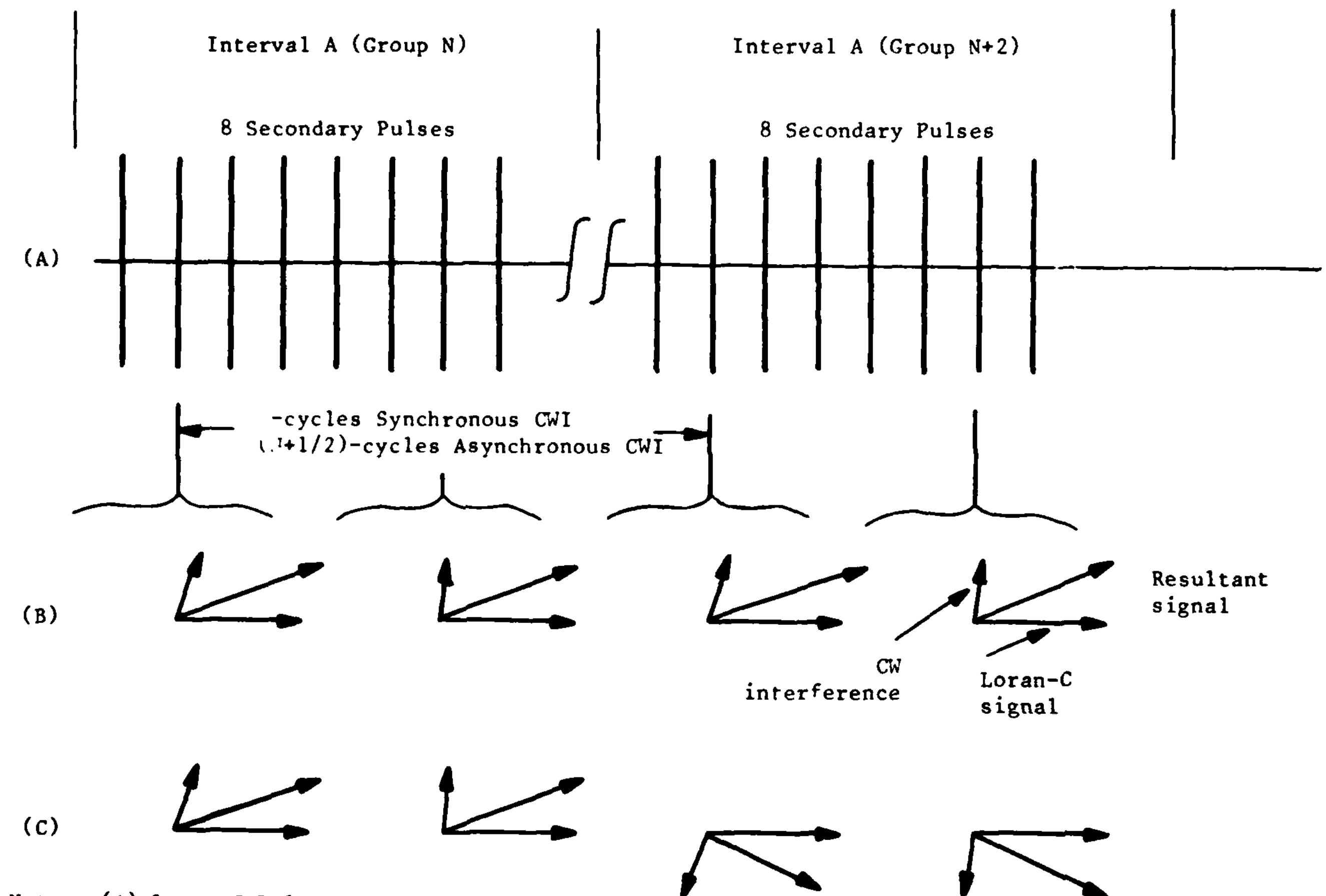
A-3 Definition and Description of Synchronous and Asynchronous Interference

The terms synchronous and asynchronous interference as applied to this report are defined with reference to Figure A-3. Selecting one pulse in the A GRI, synchronous interference is defined as a CW signal which interferes with the same relative phase each



Loran-C Pulse Cycle at Sample Point

FIGURE A-2. EFFECT OF CW INTERFERENCE ON A LORAN-C PULSE AT THE SAMPLE POINT



Note: (A) Loran-C Pulses
(B) Vector Resultants for Synchronous Interference
(C) Vector Resultants For Asynchronous Interference

FIGURE A-3. SIGNAL VECTORS FOR INTERVALS A AND B WITH INTERFERENCE ADDED time the selected pulse occurs in the A interval. This condition occurs when the interfering signal has an integral number of cycles between the repetitions of the selected LORAN-C pulse.

The uniformity with which the LORAN-C pulses occur implies that a synchronous frequency for the selected A GRI pulse will be synchronous to all LORAN-C pulses from either the Master or Secondary, although the exact phase relationship may be different for each pulse in the A and B GRI. Synchronous interference, therefore, is a CW signal which adds a constant phase shift to each LORAN-C pulse, and hence a constant error in the measured time difference, equal to the average phase disturbance affecting all pulses in GRI A and B. Phase vector pictures for the condition of synchronous CW interference are shown below each pulse in Figure A-3, on line B.

Asynchronous interference is defined as a CW signal which disturbs the phase of a selected LORAN-C pulse in two adjacent A GRIs in such a manner that the average phase disturbance is 0. This occurs when the phase of the interfering CW signal slips an odd number of 1/2 cycles over a period of 2 GRI. The phase diagrams for this case are shown in Figure A-3, line C. Synchronous interference occurs when the frequency of the CW signal is a multiple of:

$$\frac{1}{2\ \mathrm{GRI}}$$

because the allowable GRIs are multiples of 10 microseconds and 1/2 GRI will always have a harmonic at 100 kHz. Therefore, the synchronous interfering frequencies may also be expressed as spectral lines which are removed from 100 kHz by:

$$\frac{N}{2\ \mathrm{GRI}} \qquad N = 1,2,\ \ldots$$

It is further noted that all GRIs which are multiples of 100 microseconds have a common synchronous interference line at

5 kHz intervals removed from 100 kHz. This is seen as follows:

If: $GRI = (M)(100 \times 10^{-6})$

the M^{th} spectral line is:

$$f_M = \frac{100 \text{ kHz} \pm M}{2 \times M \times 10^{-4}} = 100 \text{ kHz} \pm 5 \text{ kHz}$$

Asynchronous frequencies occur when the interfering signal has an odd number of +1/2 cycles over the period of 2 GRI. Hence, asynchronous interference occurs when the CW carrier is expressible as:

$$\frac{N + 1/2}{2 \times GRI}$$

or, equivalently, at a frequency which is midway between synchronous interference frequencies.

As defined, synchronous interference adds a constant time bias to the measurement of LORAN-C time differences. Typically, however, perfect synchronism will not be maintained between the interfering signal and the LORAN-C system 100 kHz frequency. In this case, the CW interference will beat slowly against the received LORAN-C signal and cause low frequency variation in the receiver time differences. If the beat frequency is low enough, it will be passed by the receiver time difference averaging algorithm and cause a slow oscillation in the displayed time difference values.

The above beat frequency is related to the receiver tracking bandwidth and, for a receiver which has an averaging time of approximately 10 seconds, the receiver will start to reject beat frequencies when the difference between the interference and the LORAN-C signal synchronous frequency exceeds .016 kHz. Frequencies which are not asychronous and which are so far removed from synchronism that they are not tracked by the receiver, are referred to in this report as non-synchronous interference. When the relatively small receiver tracking bandwidth ($\pm$.016 Hz for a typical

10-second time constant) is compared to the approximate 5 Hz spacing between synchronous interference frequencies, it is seen that typical LORAN-C interference will be non-synchronous except in those cases where the transmission originates from a precisely controlled communication or navigation station.

APPENDIX B

MEASUREMENT OF RECEIVER PERFROMANCE UNDER LABORATORY SIMULATED LORAN-C SIGNALS AND INTERFERENCE

A series of laboratory measurements were made of the performance of the Texas Instruments 9000A LORAN-C receiver subjected to a simulated LORAN-C signal with added continuous wave interference.

The purpose of these measurements was to

1. Determine the specific effect synchronous and near synchronous interference has on the behavior of a typical marine LORAN-C receiver,

2. Establish procedures and observations to be followed during interference measurements at the airports, and

3. Put in perspective the results of the interference measurements made at the airports in Boston, Massachusetts and Burlington, Vermont.

All measurements were made with only one LORAN-C receiver, the Texas Instruments 9000A LORAN-C receiver, connected as shown in Figure B-1.

An EPSCO signal generator was used to simulate a LORAN-C (GRI = 9930) chain with two secondaries having an emission delay of 15,000 μsec and 30,000 μsec. The power level of the LORAN-C signal was adjusted to give a reading of signal-to-noise ratio of +5 dB, or 995 as displayed on the Texas Instruments receiver. The actual power level in dBm into the antenna coupler of the receiver was not measured. The continuous wave interference was applied to an input connector on the EPSCO simulator where it was added to the LORAN-C signal. The power level of the injected interference was -10 dBm at the input to the simulator, which resulted in a peak amplitude of interference equal to the LORAN-C signal peak amplitude. The signal-to-interference ratio was then 0 dB. White noise may also be added to the simulated LORAN-C signal but since these measurements concerned interference only, this variable was eliminated. A number of interfering frequencies were selected,

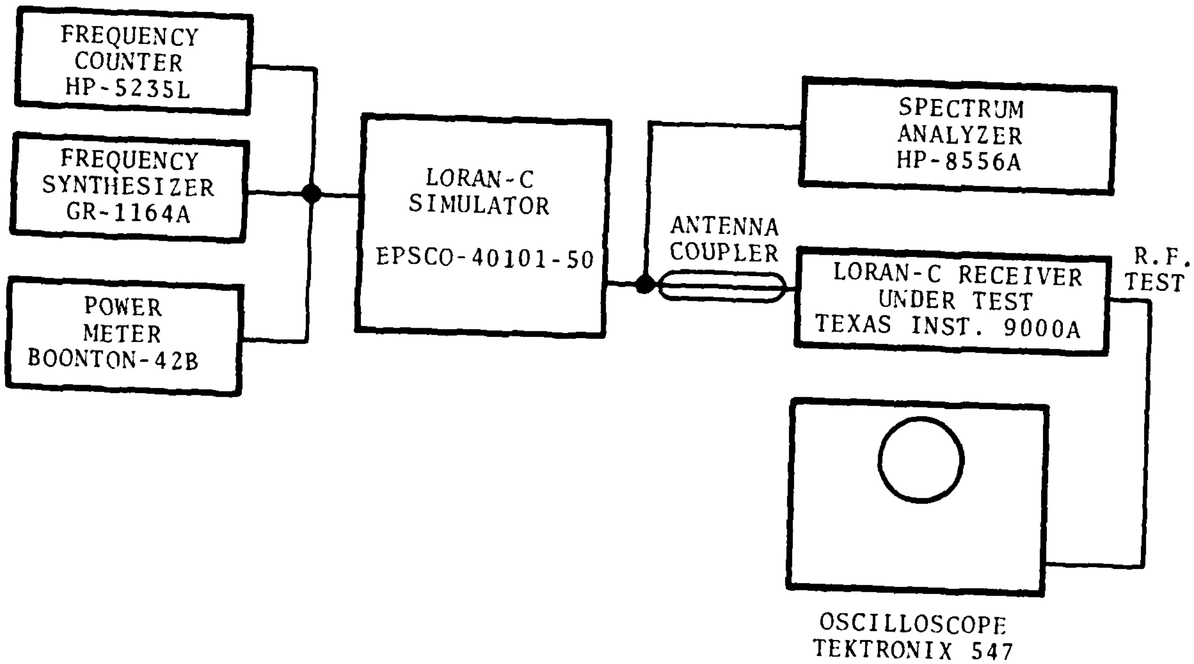


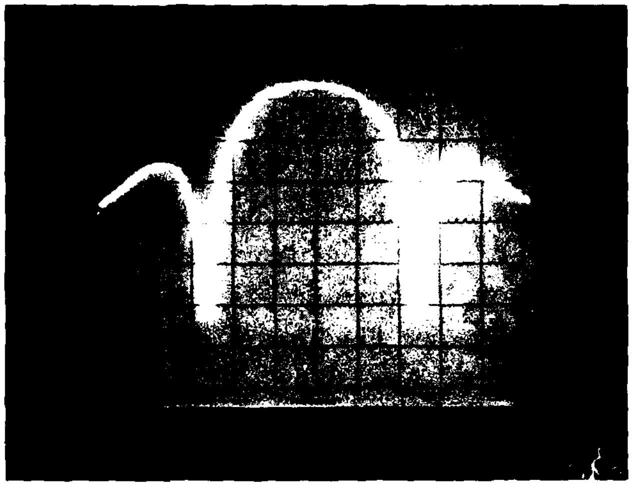
FIGURE B-1. TEST CONFIGURATION FOR LABORATORY MEASUREMENTS OF INTERFERENCE both in and out of the LORAN-C signal bandwidth (90 to 110 kHz), but still within the bandwidth of the Texas Instruments receiver. The frequency response bandwidth of the Texas Instruments receiver is shown in Figure B-2(a). Of the four internal notch filters, two are not adjustable and are set at 86 kHz and 115 kHz. The two which are adjustable (but only with the cover removed) were adjusted to each of the preset frequencies, making the original 30 dB notches become much deeper, down 60 dB from the band pass response without the filters. The smoother frequency response of this receiver can be compared to the bandpass frequency responses of the other three receivers as shown in Figure 3-4.

Figure B-2(b) is a spectrum photograph of the simulated LORAN-C signal including an interference spike at 110 kHz. The interference is adjusted to be 10 dB higher than the peak of the LORAN-C spectrum. In general, most interfering spikes lie 20 to 40 dB below the LORAN-C peak and these do not cause degraded reception. It has been verified experimentally (albeit it is somewhat obvious) that both the amplitude and frequency of the interference are important factors in determining the severity of the interference. For immediate and easily identified effects to manifest themselves, the interference amplitude should be higher than the LORAN-C peak for out-of-band frequencies. For interference within the LORAN-C bandwidth, spike amplitudes 10 dB below the LORAN-C peak will produce the recognized effects.

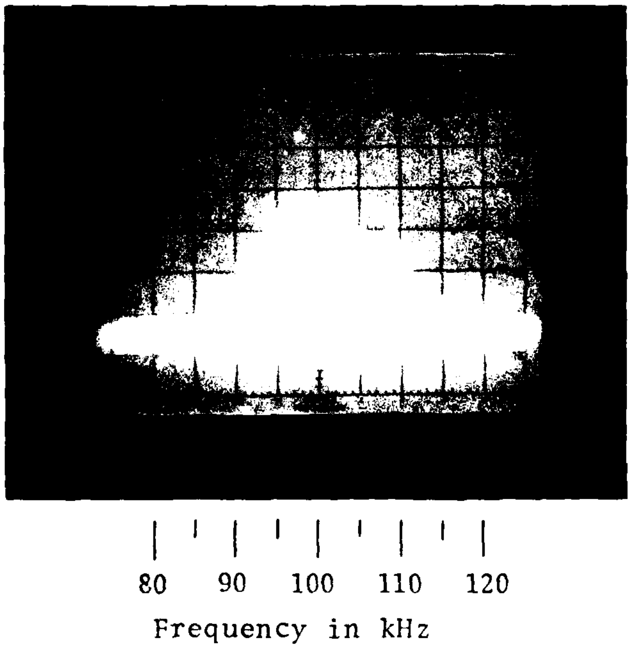
Table B-1 lists the results of these measurements as a function of frequency and power level of the interference.

From the results of these laboratory measurements the following conclusions can be drawn.

1. The presence of momentary interference, either synchronous or near-synchronous, is evidenced by the signal-to-noise ratio (displayed by the receiver) dropping immediately.



Frequency response of Texas Instruments 9000A LORAN-C receiver after aligning two adjustable notch filters with the two preset filters.



LORAN-C Frequency spectrum plus interference spike at 110 kHz fed into antenna coupler of LORAN-C receiver

Power level adjusted for SNR = 995 without interference

FIGURE B-2. FREQUENCY RESPONSE OF TEXAS INSTRUMENTS LORAN-C RECEIVER AND THE LORAN-C SPECTRUM

TABLE B-1. RESULTS OF THE LABORATORY MEASUREMENTS OF SIMULATED LORAN-C SIGNALS AND INTERFERENCE ON THE PERFORMANCE OF A LORAN-C RECEIVER

Power level -20 dBm simulator

Frequency	SNR	Acquisition Time	Time Delay Jitter	Alarm Lights	Comments
60 kHz	955	2'30"	NO		
65	957	2'20"	NO	NO	
70	952	2'15"	NO		
75	957	2'30"	NO	NO	
80	960	2'20"	NO	NO	
85	953	2'10"	NO	NO	
90	945	2'10"	NO	NO	
95	650	10'	YES		
100	690	2'45"	YES	CYC	
105	767	5'05"	YES	CYC	
110	952	4'40"	NO	NO	
115	945	2'30"	NO	NO	
120	950	2'35"	NO	NO	
91	945	7'10"		CYC	
91.500	860	10'	YES	CYC	CYC slip
91.250	935	10'	YES	CYC	CYC slip
91.500	753	10'	YES	CYC & SNR	CYC slip
95.00125	780	10'	YES	CYC & SNR	CYC slip

Power level -10 dBm into simulator

Frequency	SNR	Acquisition Time	Time Delay Jitter	Alarm Lights	Comments
60	951	1'40"	NO	NO	
65	941	2'30"	NO	NO	
70	947	2'35"	YES	NO	
75	951	after 10'	YES	CYC	
80	920	6'10"	YES	NO	
85	955	after 10'	YES	CYC	
90	736	6'30"	YES	CYC	
95	600	after 10'			Cycle between mode 0 and 3 not tracking.
100	600	after 10'	YES		Cycle between mode 0 and 3 not tracking.
105	600	after 10'	YES		Cycle between mode 0 and 3 not tracking.
110	786	after 10'	YES	CYC	
115	952	after 9'10"	YES	NO	
120	883	after 10'	YES	CYC	

2. If an uncontaminated measurement of signal-to-noise can not be made, i.e., interference cannot be turned off, then a clean SNR measurement can be inferred by the signal strength of the LORAN-C signal. The presence of interference will be indicated by an unusually low SNR displayed for the amount of LORAN-C signal available as shown on a spectrum analyzer.

3. To be classified "significant", interference must be sufficient to cause the measured time difference readings to vary from their values without the interference. The ultimate goal of the LORAN-C radio navigational system is to present correct time difference readings in the presence of noise and interference. Therefore, this was the primary criteria for determining the severity of the interference and its classification as "significant". For this report, abnormal jitter in the time difference reading is the definition of significant interference. Therefore, significant" interference will cause the time difference readings to vary greater than the ±0.1 μsec characteristic of a marine LORAN-C receiver.

The frequency of the interfering signal could have been made synchronous by phase locking the General Radio frequency synthesizer to the 10 MHz crystal oscillator in the EPSCO simulator, but this was considered unnecessary because at the airports synchronism by phase locking of an interfering source to the LORAN-C signal itself is unlikely. All of the test frequencies were adjusted to be within ±1.0 Hz of the adjacent LORAN-C spectral line by watching the beat frequency as displayed on an oscilloscope.

APPENDIX C

MAKING CALIBRATED EMI MEASUREMENTS WITH A SPECTRUM ANALYZER

For this series of EMI measurements, a Hewlett Packard spectrum analyzer Model 3585 was used exclusively in conjunction with the Bayshore antenna and coupler UPS-191B-1 to measure the radiated electric field strength.

Normally, to make radiated EMI measurements, a calibrated tuned radio receiver and antenna are required. The tuned receiver may be replaced with a spectrum analyzer that reads voltage, but the antenna factor must be determined to convert from voltage to field intensity. For example, consider a 1 meter vertical antenna in a uniform field of 1 volt/meter. A vertical conducting rod causes a uniform electric field to warp (equipotential lines are shorted out) as shown in Figure C-1. Since the rod shorts the normalized 1 volt/meter, a high impedance voltmeter placed between the rod and ground would measure 1/2 volt. For this example, the antenna factor would be 1 volt per meter per 1/2 volt, or 6 db per meter.(6)*

For the 8 inch stub antenna mounted on the roof of the LORAN-C Mobile Test Facility the antenna factor is computed as follows:

antenna factor = K = (effective height of antenna) plus (gain of the coupler).
where effective height = 1/2 actual height, and the coupler gain is determined by measurement.

The spectrum analyzer is calibrated in dBm, so a conversion to voltage is required. To read in dBuv. (dB above a microvolt) add 107 dB to the reading in dBm.

$$\text{dBuV} = \text{dBm} + 107 \text{ dB (50 ohm system)}$$

*Hewlett-Packard Application Note 150-10. Spectrum Analysis Field Strength Measurement.

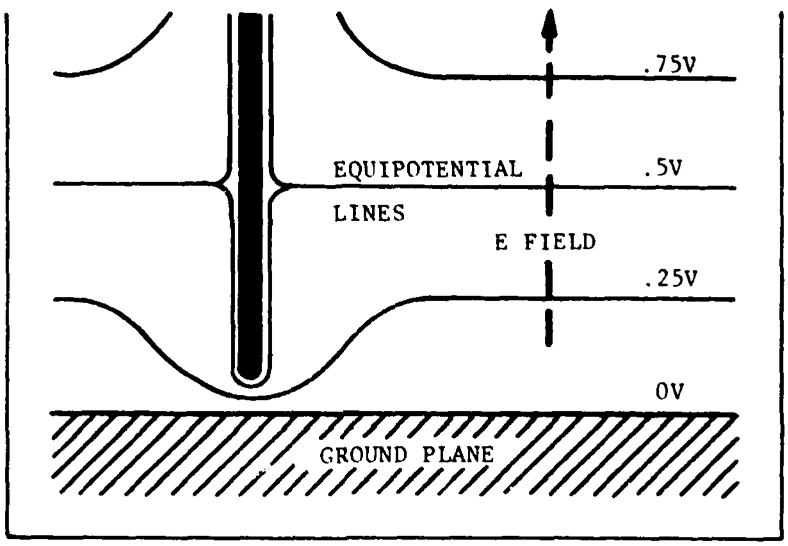


FIGURE C-1. DERIVATION OF ANTENNA FACTOR FOR 1-METER ROD

The gain of the Bayshore UPS-191B-1 antenna coupler has been measured as 26 dB, therefore the antenna factor is calculated by substituting the correct values in the following:

$$K = 1/2(0.203 \text{ meters}) + 26 \text{ dB},$$

$$K = 20 + 26 = 46 \text{ dB}.$$

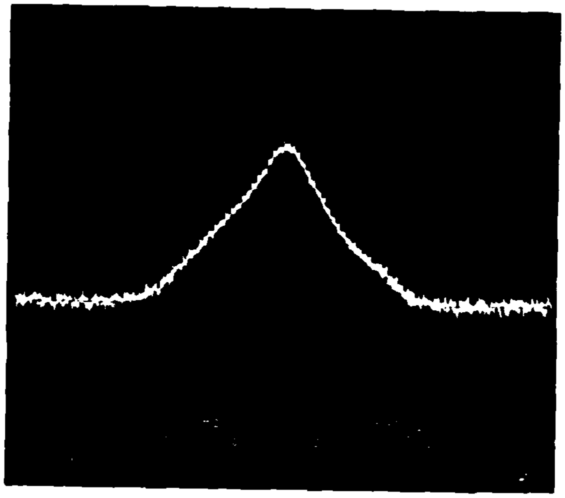
To obtain the electric field intensity in dB above 1 microvolt/meter, the following equations are used:

$$\begin{matrix}\text{Electric Field Intensity in} \\ \text{dB above 1 } \mu\text{v per meter}\end{matrix} = \begin{matrix}\text{Analyzer} \\ \text{Reading}\end{matrix} + \begin{matrix}\text{Conversion} \\ \text{to dB}\end{matrix} + \begin{matrix}\text{Antenna} \\ \text{Factor}\end{matrix}$$

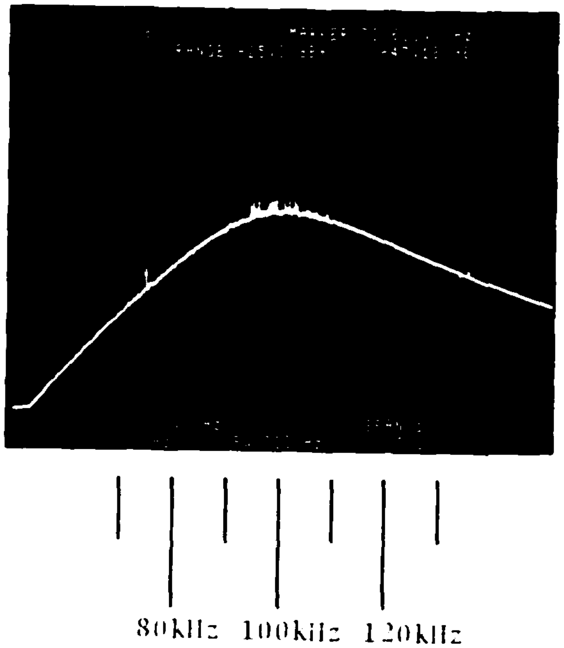
$$E = \text{Analyzer Reading} + 107 \text{ dB} + 46 \text{ dB}.$$

$$E = (\text{Analyzer})\text{dB} + 153 \text{ dB above } 1\ \mu\text{V/meter}$$

The previous analysis assumes a flat frequency response over the bandwidth of interest, in this case, 50 to 150 kHz. The spectrum analyzer is designed for a calibrated display and has a flat frequency response but the antenna coupler does not. Figure C-2 shows the actual frequency response of the antenna coupler as measured by the spectrum analyzer. This measurement was performed by feeding a signal out of the tracking oscillator to the antenna coupler with a loosely coupled (one turn) length of wire around the blade antenna. The normal mounted position of the antenna is on top of the TSC LORAN-C Mobile Test Facility. The signals in the LORAN-C band are measurable by the spectrum analyzer as shown by the curve in the bottom photograph of Figure C-2, which is the bandpass of the antenna plus coupler meter. At 70 kHz, the coupler's response is down 5 dB. At 130 kHz, it is down 3 dB. This roll-off is ignored for all amplitude measurements in this report, including those of Table 5-2. The frequency response of the measuring system is assumed to be flat for convenience. The difference of up to 5 dB at the edge of the response curve is ignored because the measurements of interest are centered in the center of the pass band where the frequency response is flat.



a) LORAN-C spectrum envelope obtained from a LORAN-C simulator



b) Antenna and coupler bandpass using a tracking oscillator and spectrum analyzer to sweep out the bandpass of the antenna system

FIGURE C-2. THE LORAN-C SPECTRUM ENVELOPE AND THE FREQUENCY RESPONSE OF THE ANTENNA SYSTEM

The upper photograph of Figure C-2 is an envelope of a LORAN-C spectrum as produced by a LORAN-C simulator connected to the input of the spectrum analyzer. The simulator was set to the SS 3 rate (Group Repetition Interval of 9970)with TDA set at 11,000 microseconds and TDB set to 30,000 microseconds. It is obvious from both photographs in Figure C-2 that the LORAN-C signal is attenuated a small amount by the bandpass characteristics of the antenna coupler. Figure C-3 shows the frequency response of the Bayshore antenna coupler as supplied by the manufacturer. It agrees with the measured response curve in Figure C-2 very well.

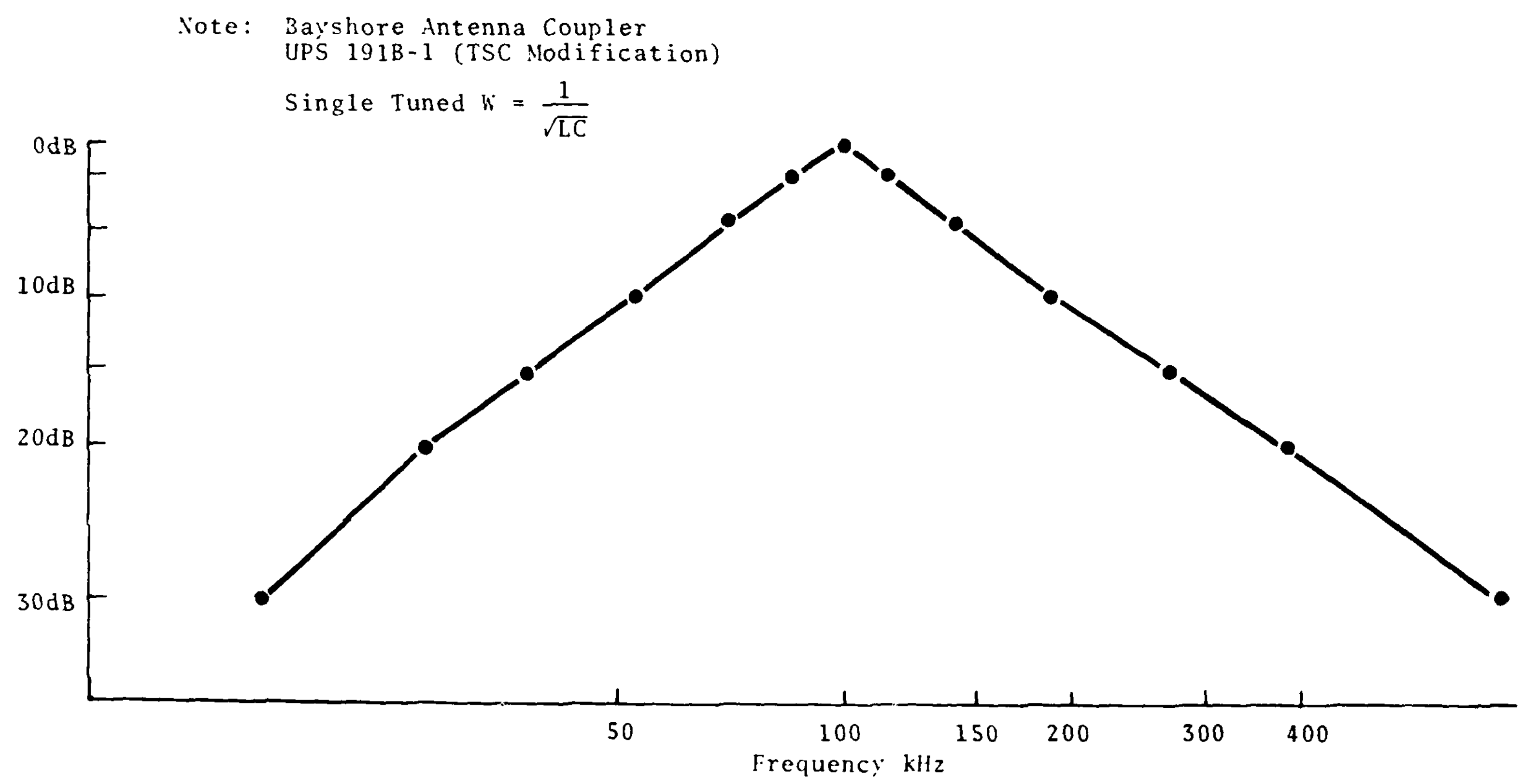


FIGURE C-3. FREQUENCY RESPONSE OF THE BAYSHORE ANTENNA COUPLER

APPENDIX D
MEASUREMENT DATA

Acquisition Time Data Sheet

LOCATION: LOGAN point 1 DATE: 9-27-79

TDA 14043.8 TDB 25873.2

	TDA	TDB	CORRECTED TDA		CORRECTED TDB	
	EPSCO -	4010	Min	Sec	Min	Sec
1	5	7	2'	40"	2'	40"
2	8	8	2	43	2	40
3	5	5	2	47	2	43
4	5	5	2	15	2	47
5	7	7	2	30	2	15
	TEXAS INSTRUMENTS 9000A					
1	45	70	1	25	1	30
2	70	30	1	55	1	55
3	30	25	1	15	1	15
4	25	45	1	10	1	10
5	45	45	1	15	1	30
	MICROLOGIC ML-200					
1	30	30	2	45	3	10
2	30	25	3	35	5	20
3						
4						
5						
	INTERNAV LC-204					
1	8	8	6	45	4	35
2						
3						
4						
5						

Acquisition Time Data Sheet

LOCATIONL LOGAN point 1 DATE: 8-27-79

TDA 14043 TDB 25871

	TDA	TDB	CORRECTED TDA				CORRECTED TDB			
	EPSCO	- 4010	Min	Sec	Min	Sec	Min	Sec	Min	Sec
1	10	30	1'	15"	1'	20"	1'	30"	1'	30"
2	15	15	1	45	1	20	1	45	1	40
3	10	10	1	10	1	40	1	30	2	00
4	10	10	1	15	1	20	1	35	1	35
5	20	15	1	25	1	30	1	50	1	35
	TEXAS INSTRUMENTS 9000A									
1	30	25	1	50	1	15	2	00	1	20
2	32	33	1	40	1	20	1	50	1	25
3	25	45	1	15	1	30	1	25	1	33
4	35	55	1	20	1	45	1	22	1	38
5	35	40	1	15	1	30	1	20	1	35
	MICROLOGIC ML-200									
1	25	35	3	10	3	05	3	15	4	40
2	30	20	3	40	3	25	4	35	3	40
3	20	30	2	20	4	00	5	00	4	00
4	35	35	3	00	3	25	5	00	3	00
5	45	25	3	35	3	20	6	00	3	30
	INTERNAV LC-204									
1	15	15	5	10	5	30	4	30	4	50
2	18	10	6	50	6	45	3	35	4	45
3	10	15	5	55	4	55	4	00	6	15
4	22	10	6	10	6	05	6	0	5	10
5	10	12	5	75	5	40	4	50	3	55

Acquisition Time Data Sheet

LOCATION: LOGAN SUBWAY DATE: 9-27-79

TDA 14040.0 TDB 25881.0

	TDA	TDB	CORRECTED TDA		CORRECTED TDB	
	EPSCO - 4010		Min	Sec	Min	Sec
1	5 sec.	5 sec.	2'	05"	2'	05"
2	7 sec.	7 sec.	1	50	1	50
3	5 sec.	5 sec.	1	40	1	40
4	5 sec.	5 sec.	2	10	2	10
5	5 sec.	5 sec.	2	15	2	15
	TEXAS INSTRUMENTS 9000A					
1	25	25	1	15	1	15
2	40	40	1	20	1	20
3	30	30	1	15	1	15
4	30	30	1	20	1	20
5	35	30	1	15	1	15
	MICROLOGIC ML-200					
1	45	45	3	30	3	30
2	30	30	3	40	3	25
3	25	25	3	50	3	20
4	30	35	>7 min.		3	15
5	35	35	>7 min.		3	25
	INTERNAV LC-204					
1	15	25	>7 min.		4	50
2	20	20	>7 min.		5	10
3	30	30	>7 min.		4	30
4	25	25	>7 min.		6	30
5	20	20	>7 min.		4	25

Acquisition Time Data Sheet

LOCATION MPV DATE: 9-26-79

With notch Filters Set TDA 14067.7 TDB 26994.6

	TDA	TDB	CORRECTED TDA		CORRECTED TDB	
	EPSCO - 4010		Min	Sec	Min	Sec
1	8	8	1'	15"	1'	15
2	8	8	2	50	2	50
3	10	10	2	10	2	10
4	8	8	2	05	2	05
5	10	10	3	20	3	20
	TEXAS INSTRUMENTS 9000A					
1	38	38	1	20	1	15
2	42	42	1	35	1	35
3	75	75	2	10	2	05
4	40		1	30	1	30
5	30		1	25	1	25
	MICROLOGIC ML-200					
1	55	45	3	05	3	20
2	40	45	4	05	4	10
3	25	35	3	20	3	45
4						
5						
	INTERNAV LC-204					
1	10	12	6	05	4	45
2	10	10	6	20	3	40
3	8	8	7	05	4	20
4						
5						

Acquisition Time Data Sheet

No Notches LOCATION: BURLINGTON RWY 1 DATE: 9-25-79

TDA 4227.1 TDB 27257.8

	TDA	TDB	CORRECTED TDA		CORRECTED TDB	
	EPSCO - 4010		Min	Sec	Min	Sec
1	10		2'	20"	2'	20"
2	10		2	40	2	50
3	12		2	05	2	05
4	8		2	10	2	10
5	8		1	55	1	55
	TEXAS INSTRUMENTS 9000A					
1	25		1	15	1	15
2	17		1	05	1	05
3	18		1	15	1	15
4	35		1	25	1	25
5	45		1	20	1	20
	MICROLOGIC ML-200					
1	30	45	3	05	4	45
2	18	35	3	10	3	30
3	20	30	3	10	3	15
4	25	30	3	15	4	55
5	20	25	3	05	3	10
	INTERNAV LC-204					
1	10	10	7	10	5	20
2	12	15	7	0	5	10
3	8	12	6	30	4	40
4	8	10	6	50	5	45
5	10	12	7	10	5	30

Acquisition Time Data Sheet

LOCATION: BURLINGTON SURVEY PT DATE: 9-26-79

with notch filters TDA 14224.4 TDB 27256.3
set at 88 and 113.1

	TDA	TDB	CORRECTED TDA		CORRECTED TDB	
	EPSCO - 4010		Min	Sec	Min	Sec
1	10		1'	45"	1'	45"
2	5		1	35	1	35
3	5		1	40	1	40
4	8		1	25	1	25
5	5		1	35	1	35
	TEXAS INSTRUMENTS 9000A					
1						
2						
3						
4						
5						
	MICROLOGIC ML-200					
1	20		3	10	3	00
2	25		2	45	3	40
3	30		3	20	3	20
4	20		3	15	3	20
5	25		3	20	3	25
	INTERNAV LC-204					
1	45		7	30	4	50
2	10		7	35	4	10
3	10		7	10	3	50
4	5		6	45	3	50
5	8		6	50	3	45

Acquisition Time Data Sheet

No Notches LOCATION: BURLINGTON SURVEY PT DATE: 9-24-79 PM

TDA TDB

	TDA	TDB	CORRECTED TDA Min	CORRECTED TDA Sec	CORRECTED TDB Min	CORRECTED TDB Sec
	EPSCO - 4010					
1	8		2'	45"	1'	50"
2	8		2	20	1	55
3	8		2	35	2	50
4	7		1	40	1	50
5	15		2	05	2	10
	TEXAS INSTRUMENTS 9000A					
1	55		1	55	1 55	55
2	60		2	00	1 00	00
3	35		1	30	1 15	15
4	35		0	50	0 50	50
5	25		0	40	0 40	40
	MICROLOGIC ML-200					
1	30		3	25	4	05
2	25		3	10	3	25
3	30		3	20	3	50
4	35		3	30	3	45
5	30		3	30	3	00
	INTERNAV LC-204					
1	7		6	50	4	35
2	10		6	40	4	10
3	13		6	05	4	10
4	10		6	45	4	05
5	10		6	40	4	00

Acquisition Time Data Sheet

No Notches LOCATION: AIR NORTH BURLINGTON DATE: 9-25-79

TDA 14227.2 TDB 27259.1

	TDA	TDB	CORRECTED TDA Min	CORRECTED TDA Sec	CORRECTED TDB Min	CORRECTED TDB Sec
	EPSCO-4010					
1	10		1'	55"	2'	00"
2	5		1	50	1	58
3	7		2	00	2	10
4	8		2	30	2	30
5	7		2	00	2	00
	TEXAS INSTRUMENTS 9000A					
1	45		1	35	1	35
2	40		1	25	1	25
3	20		1	10	1	10
4	45		1	05	1	05
5	40		1	25	1	25
	MICROLOGIC ML-200					
1	15		3	40	5	30
2						
3						
4						
5						
	INTERNAV LC-204					
1	7		6	00	8	45
2	10		6	10	7	25
3						
4						
5						

Acquisition Time Data Sheet

No Notches LOCATION: BURLINGTON SURVEY POINT DATE: 9-25-79 AM

TDA 14224.1 TDB 27256.5

	TDA	TDB	CORRECTED TDA	CORRECTED TDB
	EPSCO - 4010		Min Sec	Min Sec
1	8		1' 40"	1' 40"
2	6		1 30	1 30
3	5		2 05	2 05
4	8		2 10	2 10
5	4		2 40	2 40
	TEXAS INSTRUMENTS 9000A			
1	55		1 40	1 40
2	60		1 30	1 30
3	45		1 35	1 35
4	35		1 30	1 30
5	60		1 35	1 35
	MICROLOGIC ML-200			
1	15		2 45	4 35
2	30		3 10	4 45
3	30		3 05	3 40
4	35		2 50	3 30
5	25		2 55	3 35
	INTERNAV LC-204			
1	7		7 10	4 30
2	12		6 15	4 40
3	5		7 25	4 55
4				
5				

TAPE E RUN NUMBER 1 DATE 9/25/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14227.3	27249.5	1.11	5881	4	4
AIR NORTH TERMINAL @ BURLINGTON 11:00 AM					
14227.3	27249.5	1.11	5831	4	4
14227.3	27249.5	1.11	5881	4	4
14227.2	27249.5	1.89	0000	4	4
14227.3	27249.5	1.89	0000	4	4
14227.2	27249.5	1.89	0000	4	4
14227.2	27249.6	1.89	0000	4	4
14227.3	27249.6	1.89	0000	4	4
14227.3	27249.6	1.89	0000	4	4
14227.3	27249.4	1.89	0000	4	4
14227.4	27249.6	1.89	0000	4	4
14227.3	27249.7	1.89	0000	4	4
14227.3	27259.6	1.89	0000	4	4
14227.3	27259.6	1.89	0000	4	4
14227.3	27259.5	1.89	0000	4	4
14227.2	27259.6	1.89	0000	4	4
14227.3	27249.6	1.89	0000	4	4
14227.3	27249.6	1.89	0000	4	4
14227.2	27259.6	1.89	0000	4	4
14227.3	27249.5	1.89	0000	4	4
14227.3	27249.5	1.89	0000	4	4
14227.2	27249.5	1.89	0000	4	4
14227.3	27249.5	1.89	0000	4	4
14227.3	27249.5	1.89	0000	4	4
14227.2	27249.5	1.89	0000	4	4
14227.3	27249.6	1.89	0000	4	4
14227.3	27249.6	1.89	0000	4	4
14227.3	27249.5	1.89	0000	4	4
14227.2	27249.5	1.89	0000	4	4
14227.3	27249.5	1.89	0000	4	4
14227.3	27249.6	1.89	0000	4	4

TAPE E RUN NUMBER 2 DATE 9/25/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14226.8	27255.4	0.00	0000	4	4
THRESHOLD OF RUNWAY 15 @ BURLINGTON			12 NOON		
14226.8	27253.4	9.00	0000	4	4
14226.8	27255.3	0.00	0000	4	4
14226.8	27255.4	0.00	0000	4	4
14226.9	27255.3	0.00	0000	4	4
14226.9	27255.3	0.00	0000	4	4
14226.8	27255.4	0.00	0000	4	4
14226.8	27255.4	0.00	0000	4	4
14226.8	27255.3	0.00	0000	4	4
14226.8	27255.2	0.00	0000	4	4
14226.7	27255.2	0.00	0000	4	4
14226.8	27255.3	0.00	0000	4	4
14226.8	27255.3	0.00	0000	4	4
14226.8	27255.2	0.00	0000	4	4
14226.8	27255.2	0.00	0000	4	4
14226.8	27255.3	0.00	0000	4	4
14226.8	27255.2	0.00	0000	4	4
14226.8	27255.3	0.00	0000	4	4
14226.8	27255.2	0.09	0000	4	4
UL SLIPED CYCLE NONCORRECTED					
14226.8	27255.2	0.09	0000	4	4
14226.9	27255.3	0.00	0000	4	4
14226.8	27255.3	0.00	0000	4	4
27255.4	27255.3	0.00	0000	4	4
27253.3	27255.3	0.00	0000	4	4
27255.2	27255.2	0.00	0000	4	4
27245.2	27275.2	0.00	0000	4	4
27255.2	27245.2	0.00	0000	4	4
27265.2	27255.1	0.00	0000	4	4
14226.8	27265.1	0.00	0000	4	4
14226.8	27265.2	0.00	0000	4	4

TAPE E RUN NUMBER 5 DATE 9/26/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14224.3	27256.7	0.00	0000	4	4
WED 9:00 AM TIME TO LOCK WITH NOTCHES @ 113.1 & 88 KHZ					
14224.3	27256.6	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.4	27256.5	0.00	0000	4	4
14224.4	27256.5	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.4	27256.5	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.3	27256.7	0.00	0000	4	4
14224.4	27256.6	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.3	27256.7	0.00	0000	4	4
14224.3	27256.7	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.4	27256.5	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.4	27256.6	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.3	27255.7	0.00	0000	4	4

TAPE E RUN NUMBER 6 DATE 9/26/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14068.1	26994.7	0.00	0000	4	4
14068.2	26994.8	0.00	0000	4	4
MONTPELIER SERVEY POINT WITH NOTCHES @ 88 & 113.1 KHZ					
14068.2	26994.8	0.00	0000	4	4
14068.0	26994.7	0.00	0000	4	4
14068.1	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.6	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.7	0.00	0000	4	4
14068.0	26994.7	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14067.9	26994.8	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.0	26994.9	0.00	0000	4	4
14068.0	26994.7	0.00	0000	4	4
14068.0	26994.7	0.00	0000	4	4
14068.1	26994.8	0.00	0000	4	4
14068.1	26994.8	0.00	0000	4	4
14068.0	26994.9	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4
14068.1	26994.8	0.00	0000	4	4
14068.0	26994.7	0.00	0000	4	4
14068.1	26994.8	0.00	0000	4	4
14068.0	26994.6	0.00	0000	4	4
14068.0	26994.8	0.00	0000	4	4

TAPE E   RUN NUMBER 7   DATE 9/24/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14059.3	26991.4	0.00	0000	4	4
MPU RUNWAY 35					
14069.2	26991.4	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.3	26991.4	0.00	0000	4	4
14069.2	26991.6	0.00	0000	4	4
14069.3	26991.5	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.2	26991.4	0.00	0000	4	4
14069.3	26991.5	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.2	26991.4	0.00	0000	4	4
14069.2	26991.6	0.00	0000	4	4
14069.3	26991.5	0.00	0000	4	4
14069.2	26991.4	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.2	26991.4	0.00	0000	4	4
14069.3	26991.4	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.3	26991.4	0.00	0000	4	4
14069.3	26991.5	0.00	0000	4	4
14069.2	26991.5	0.00	0000	4	4
14069.3	26991.5	0.00	0000	4	4
14069.1	26991.4	0.00	0000	4	4
MPU RUN WAY 23					
14.0	26991.4	0.00	0000	4	4
14061.8	26993.5	0.00	0000	4	4
14061.8	26993.6	0.00	0000	4	4

TAPE C   RUN NUMBER 1   DATE 9/24/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
SURVEY POINT @ BURLINGTON APT 5:30PM					
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.1	27256.6	0.00	0000	4	4
14224.1	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.3	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.1	27256.6	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4

TAPE C RUN NUMBER 2 DATE 9/25/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14224.3	27256.4	0.00	0000	4	4
SURVEY POINT @ BURLINGTON AIRPORT 8:00 AM					
14224.3	27256.4	0.00	0000	4	4
14224.2	27256.4	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.4	0.00	0000	4	4
14224.3	27256.4	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.3	27256.5	0.00	0000	4	4
14224.3	27256.4	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.4	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.4	0.00	0000	4	4
14224.1	27256.6	0.00	0000	4	4
14224.1	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.3	0.00	0000	4	4
14224.2	27256.4	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.7	0.00	0000	4	4
14224.2	27256.5	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.6	0.00	0000	4	4
14224.2	27256.4	0.09	0000	4	4

TAPE C   RUN NUMBER 4   DATE 9/27/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14044.0	25872.6	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
LOGAN SITE1					
14043.9	25872.5	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14043.8	25872.5	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14044.0	25872.5	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
14043.9	25872.6	0.00	0000	4	4
14043.7	25872.6	0.00	0000	4	4
14043.7	25872.5	0.00	0000	4	4
14044.0	25872.4	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
14044.0	25872.5	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14044.0	25872.5	0.00	0000	4	4
14043.8	25872.6	0.00	0000	4	4
14043.8	25872.5	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14043.9	25872.6	0.00	0000	4	4
14044.0	25872.6	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14044.0	25872.5	0.00	0000	4	4
14043.9	25872.5	0.00	0000	4	4
14043.9	25872.6	0.00	0000	4	4

TAPE E RUN NUMBER 4 DATE 9/24/79

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
THRESHOLD OF RUN WAY 1 @ BURLINGTON 12:30					
14227.3	27258.5	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.2	27258.4	0.00	0000	4	4
14227.2	27258.4	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.2	27258.5	0.00	0000	4	4
14227.2	27258.5	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.2	27258.5	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.4	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.3	27259.6	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.2	27258.4	0.00	0000	4	4
14227.3	27258.5	0.00	0000	4	4
14227.2	27258.4	0.00	0000	4	4
14227.2	27258.4	0.00	0000	4	4
14227.3	27258.3	0.00	0000	4	4

APPENDIX E

DESCRIPTION OF DATA ACQUISITION SYSTEM FOR AUTOMATICALLY MEASURING LORAN-C PARAMETERS

E-1 Loran-C Mobile Laboratory

The mobile LORAN-C laboratory (Figure 3-1) was developed to measure LORAN-C parameters, recording LORAN-C coordinates, and odometer measured distance while the truck is driven along a roadway. It contains spectrum analyzers, precision time clocks and other laboratory equipment for measuring noise and radio frequency interference. Figure E-1 is a block diagram of the equipment configuration. The experiment is controlled by a Tektronix 4051 Graphic Computing System operating from a real-time BASIC program stored in 30K of RAM. Data are sampled at a four second rate on command from the Micrologic LORAN-C receiver. All data are loaded in parallel (broadside) to a shift register whose length is sufficient to accommodate all sources simultaneously to insure accurate tracking of distance, time and LORAN-C coordinates.

During the 4-second interval between sample commands, the data are formatted into 8-bit bytes and transmitted over the General Purpose Interface Bus to the Tektronix controller where processing and recording are accomplished before the next sample command. The data are also recorded on magnetic tape for later analysis. The software allows the operator to control navigation system mode, data gathering, memory, inspection and other system functions, all through the User Definable Keys.

Data Acquisition

The new Northeast coast chain has three operational secondary stations; at Caribou, Maine, Carolina Beach, North Carolina and Nantucket, Massachusetts. The Master is located at Seneca, New York. The two secondaries providing the optimum crossing angles, (Lines of Position) (LOP) crossing at nearly right angles in the Boston area, are Caribou and Carolina Beach. The Secondary

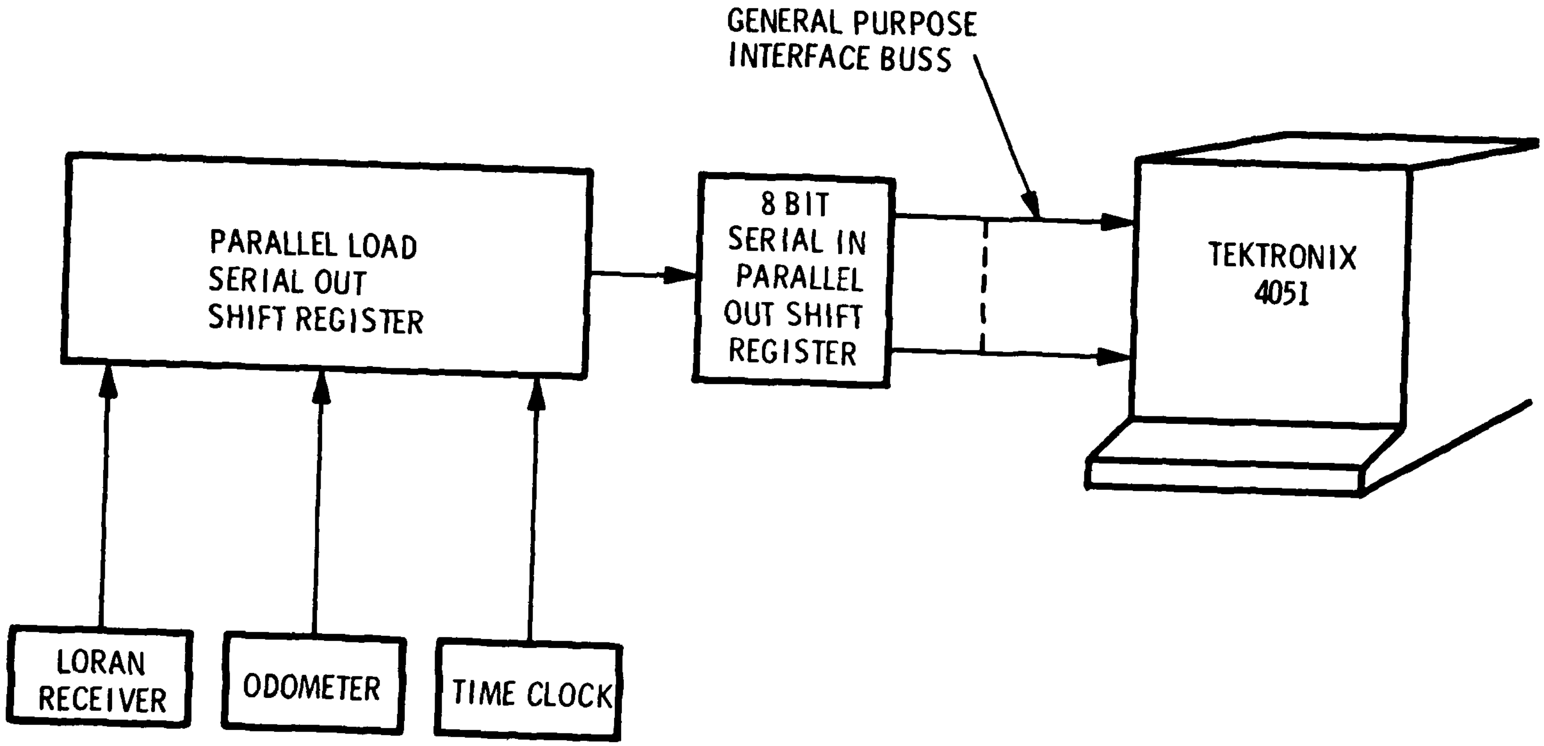


FIGURE E-1. FUNCTIONAL BLOCK DIAGRAM OF DATA ACQUISITION SYSTEM transmitter located in Nantucket provides an exceptionally strong signal; however, it is not preferred over those stations which have good crossing angles.

The data can be displayed in tabular form on the screen of the Tektronix controller as shown in Table E-1. This allows monitoring of the results as the experiment progresses. The first two columns are the time difference measurements, in microseconds, between the Master station and Secondary A(TDA) and Secondary B(TDB). The third column is the odometer measured distance to one-hundredth of a mile. Note that when the vehicle is stationary, this reading is zero. The fourth column is the odometer readout, in feet. It appears simultaneously on the data printout and on the electronic display of the odometer. Columns labeled Alarm 1 and 2 are status indicators for the LORAN-C receivers being used. A number is displayed for every possible operating mode of the receiver. Alarm 1, is associated with TDA, and Alarm 2 with TDB. The number ranges from 1 to 128 to indicate the status of the transmitter or receiver equipment. The number 4, for example, indicates both the transmitters and receivers are operating correctly.

The Tektronix 4051 is supplied with software support programs which enable a complete statistical analysis of the data collected at a fixed location, including mean, variance, standard deviation, skewness, kurtosis, etc.

TABLE E-1. LORAN EXPERIMENT DATA

RUN NUMBER 4 DATE 7/12/78

TDA	TDB	MILES	DIST.	ALARM 1	ALARM 2
14041.0	44355.0	0.00	8775	4	4
14040.9	44354.9	0.00	8776	4	4
14040.9	44354.8	0.00	8776	4	4
14040.9	44354.9	0.00	8776	4	4
14040.9	44355.0	0.00	0000	4	4
14040.8	44354.9	0.23	0000	4	4
14040.7	44354.9	0.23	0000	4	4
14040.9	44354.9	0.23	0000	4	4
14040.9	44355.0	0.00	0000	4	4
14041.0	44354.9	0.00	0000	4	4
14041.0	44354.9	0.00	0000	4	4
14040.9	44355.0	0.00	0000	4	4
14040.9	44355.0	0.00	0004	4	4
14040.9	44354.9	0.01	0047	4	4
14040.9	44354.9	0.02	0119	4	4
14041.0	44354.8	0.04	0227	4	4
14041.0	44354.8	0.07	0362	4	4
14041.2	44354.7	0.10	0519	4	4
14041.4	44354.6	0.13	0682	4	4
14041.5	44354.4	0.16	0857	4	4
14041.6	44354.1	0.20	1045	4	4
14041.8	44353.6	0.28	1454	4	4
14042.0	44353.3	0.32	1675	4	4
14042.2	44353.3	0.36	1899	4	4
14042.3	44353.1	0.40	2123	4	4
14042.6	44352.9	0.44	2349	4	4

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